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CLIMATIC VARIATIONS IN TROPICAL WEST AFRICAN RAINFALL AND THE IMPLICATIONS FOR MILITARY PLANNERS

by

Christi S. Montgomery

June 2008

Thesis Advisor: Tom Murphree
Second Reader: Michael T. McMaster

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We have identified statistical and dynamical relationships between summer rainfall variations in tropical West Africa (TWA) and El Niño/La Niña (ENLN) events in the tropical Pacific. Our primary data sets were the National Centers for Environmental Prediction / National Center for Atmospheric Research reanalysis fields and the Multivariate ENSO Index (MEI) for the period 1970-2007. Correlations of TWA rainfall and MEI time series showed that high (low) TWA rainfall was significantly correlated with LN (EN) events, with LN (EN) leading by zero to seven months. Composite analyses showed that ENLN impacts on TWA occurred via global scale equatorial Rossby-Kelvin waves and Southern Hemisphere Rossby wave trains that extended into the tropical African region. We also found regional connections between positive (negative) sea surface temperature (SST) anomalies in the Gulf of Guinea and Angola coastal waters and negative (positive) TWA rainfall anomalies. We expect our results to contribute to improved long lead rainfall predictions for TWA. This would allow military and civilian planners to construct a more effective framework for Theater Security Cooperation in TWA, including strategies for mitigating the impacts of climate variations and climate change.

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Christi S. Montgomery
Lieutenant, United States Navy
B.A., Indiana University, 1998
B.S., Indiana University, 1998
M.Eng., University of Maryland, 2003

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requirements for the degree of

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June 2008

Author: Christi S. Montgomery

Approved by: Dr. Tom Murphree
                Thesis Advisor

                Michael T. McMaster
                Second Reader

                Dr. Phil Durkee
                Chairman, Department of Meteorology

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ABSTRACT

We have identified statistical and dynamical relationships between summer rainfall variations in tropical West Africa (TWA) and El Niño/La Niña (ENLN) events in the tropical Pacific. Our primary data sets were the National Centers for Environmental Prediction / National Center for Atmospheric Research reanalysis fields and the Multivariate ENSO Index (MEI) for the period 1970-2007. Correlations of TWA rainfall and MEI time series showed that high (low) TWA rainfall was significantly correlated with LN (EN) events, with LN (EN) leading by zero to seven months. Composite analyses showed that ENLN impacts on TWA occurred via global scale equatorial Rossby-Kelvin waves and Southern Hemisphere Rossby wave trains that extended into the tropical African region. We also found regional connections between positive (negative) sea surface temperature (SST) anomalies in the Gulf of Guinea and Angola coastal waters and negative (positive) TWA rainfall anomalies. We expect our results to contribute to improved long lead rainfall predictions for TWA. This would allow military and civilian planners to construct a more effective framework for Theater Security Cooperation in TWA, including strategies for mitigating the impacts of climate variations and climate change.

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LIST OF ABBREVIATIONS, ACRONYNS, SYMBOLS, AND SPECIAL TERMS

+/+	pattern anomalously high rainfall in both the Sahel and Guinea coast regions of TWA
-/-	pattern of anomalously low rainfall in both the Sahel and Guinea coast regions of TWA
-/+	pattern of anomalously high rainfall in the Sahel region and low rainfall in the Guinea coast region of TWA
+/-	pattern of anomalously low rainfall in the Sahel region and high rainfall in the Guinea coast region of TWA
ρ	density
14WS	14th Weather Squadron (formerly known as AFCCC)
AEJ	African Easterly Jet
AEW	African Easterly Wave
AFCCC	Air Force Combat Climatology Center
AFRICOM	Africa Command
AMJ	April-May-June
APS	African Partnership Station
BES	Budget Estimate Submission
CCA	Canonical Correlation Analysis
CFFC	Commander, Fleet Forces Command
CMO	Civil-Military Operations
CNO	Chief of Naval Operations
CONOPS	Concept of Operations
CPC	Climate Prediction Center
DoD	Department of Defense
DoS	Department of State
EN	El Niño
ENLN	El Niño-La Niña
ENSO	El Niño/Southern Oscillation
ESRL	Earth Systems Research Laboratory
EUCOM	European Command

FAR	Fourth Assessment Report
FHA	Foreign Humanitarian Assistance
FNMOD	Fleet Numerical Meteorological and Oceanographic Detachment
FY	Fiscal Year
FYDP	Future Year Defense Plan
GCM	Global Circulation Model
GPH	Geopotential Height
GFS	Global Fleet Station
Guinea coast region	region of TWA bounded by 11.2°W to 9.4°E and 8.6°N to 4.8°N
HCA	humanitarian and civic assistance
hPa	hectoPascal
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
JAS	July-August-September
JPG	Joint Programming Guidance
LN	La Niña
LTM	long-term mean
mb	millibar
MEI	Multivariate ENSO Index
MET	Mobile Environmental Team
METOC	Meteorology and oceanography
MCS	mesoscale convective systems
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDAA	National Defense Authorization Act
NGO	non-governmental organization
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration
NWC	Naval War College

OGA	other governmental agency
OLR	outgoing long-wave radiation
OND	October-November-December
p	pressure
Pa	Pascal
POM	Program Objective Memorandum
PPBE	Planning, Programming, Budgeting, and Execution
PR	Program Review
PRATE	precipitation rate
RPCB	regional partner capacity building
R-K	Rossby-Kelvin
Sahel region	region of TWA bounded by 11.2°W to 9.4°E and from 12.4°N to 16.2°N
SC	security cooperation
SH	Southern Hemisphere
SLP	sea level pressure
SST	sea surface temperature, or surface skin temperature
SWMJ	Southwesterly Monsoon Jet
T	temperature
TEJ	Tropical Easterly Jet
TRB	tropical rain belt
TSC	theater security cooperation
TWA	tropical West Africa
UCP	Unified Command Plan
UN	United Nations
USAID	United States Agency for International Development
V	wind
WAM	West African monsoon
WFP	World Food Program

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I.   INTRODUCTION

A.   OVERVIEW

The variability of rainfall in tropical West Africa (TWA) has been studied during the last several decades. A swell of research interest was generated in the early 1970s by the repeated years of drought-induced famine that ravaged many of the nations in TWA and beyond. Landmark research of note includes the Burpee's (1972) work on African easterly waves (AEWs) and Nicholson's (1981, 1986) work on the modes of interannual variability in TWA rainfall. Many other distinguished researchers have continued to push the frontier of knowledge forward in the understanding of the factors that contribute to climate variability in TWA rainfall.   This study seeks to add to that effort by quantifying the relationships between TWA rainfall and global scale climate variations, especially El Niño/La Niña (ENLN), and regional scale climate variations, especially sea surface temperature (SST) variations in the African portion of the Atlantic basin. Further understanding of global and regional climate connections to TWA could potentially increase skill in predicting TWA rainfall on intraseasonal to interannual scales (weeks to years).   Increased skill in long-term predictions would allow military and government planners, including the new regional combatant command, AFRICOM, and the Departments of Defense and State, to construct a beneficial framework for Theater Security Cooperation in TWA, which addresses mitigation strategies for climate variations and long-term climate change.

B.   GEOGRAPHY

In focusing on the interannual variability of rainfall in TWA, it is helpful to have clearly defined spatial boundaries for comparison of data from year to year. Nicholson (2008a) and others have conducted extensive research on the spatial variability of TWA rainfall, and have shown that TWA tends to have a strong zonal coherence from almost 20°N to the equator.   For the purposes of this

study, precipitation rate (PRATE) time series and correlations were constructed for two separate and distinct climatic regions of TWA. The northern region, referred to as the Sahel region, ranges from 11.2°W to 9.4°E and from 12.4°N to 16.2°N. The southern coastal region, referred to as the Guinea coast region, ranges from 11.2°W to 9.4°E and 8.6°N to 4.8°N. These regions are outlined in Figure 1.

These two TWA regions are coincident with much of the United Nations (UN) subregion of West Africa, which includes 16 nations and spans the western Sahara, western Sahel, Soudan and Guinea coast (Figure 1). In this subregion, spanning approximately 20°E to 20°W, and from 20°N to the Guinea coast, the landscape transitions from the Sahara desert in the northern part of the subregion, to the grasslands of the Sahel along the southern edge of the Sahara, to the grasslands and woodlands of the upper highlands and the Soudan, and the tropical Guinea coast in the south. The variation in vegetation corresponding to these landscape transitions is evident in enhanced imagery from the Moderate-resolution Imaging Spectroradiometer (MODIS). An example of an Enhanced Vegetation Index (EVI) map for October 2001 is shown in Figure 2.
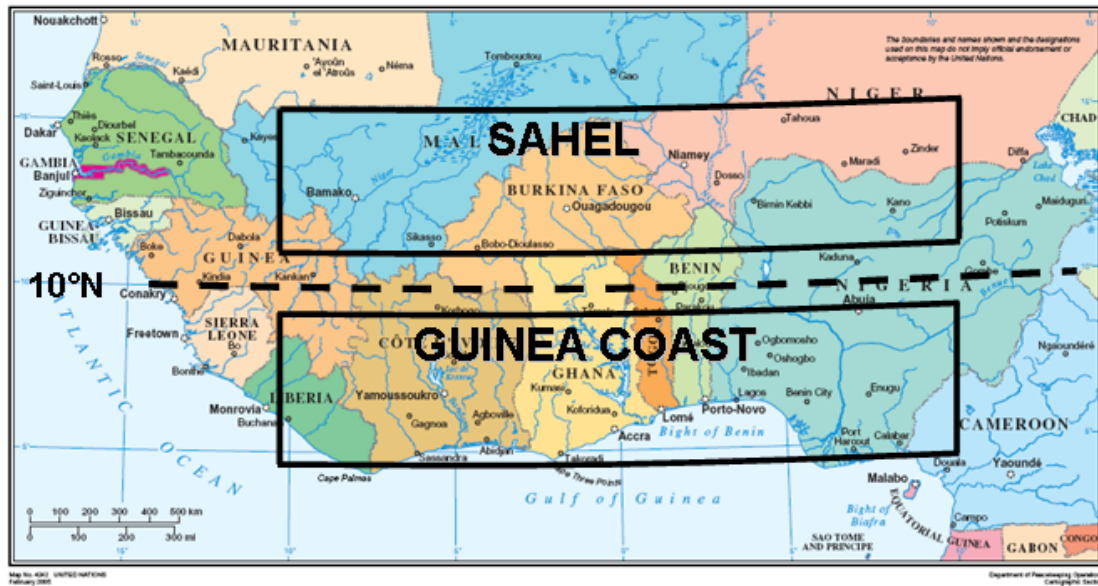
Figure 1.   Map of tropical West Africa, showing 15 of the 16 countries included in the UN subregion of West Africa. Map obtained at: http://www.un.org/Depts/Cartographic/map/profile/westafrica.pdf , accessed May 2008. The two black rectangles indicate the two focus regions of TWA for our study.
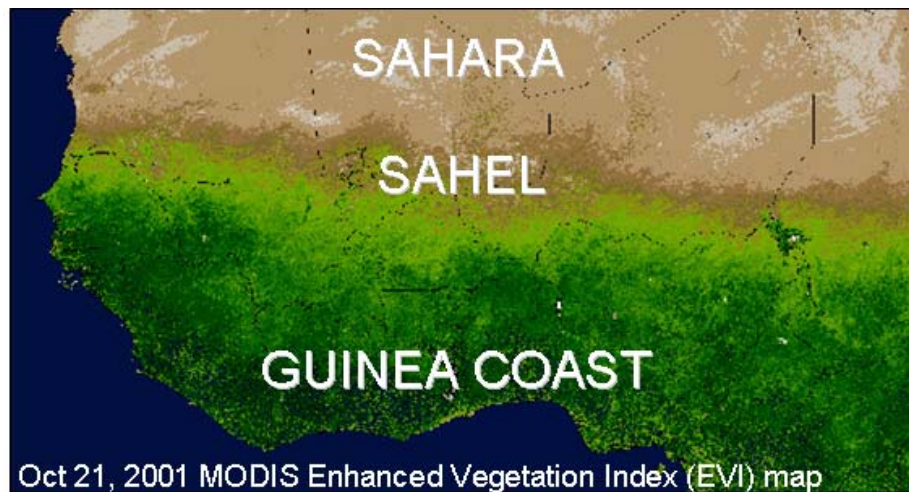
Figure 2.   MODIS Enhanced Vegetation Index (EVI) map. The Sahara, Sahel, and Guinea coast labels indicate the three main climate zones in western Africa. Map courtesy of MODIS Land Group/Vegetation Indices, Alfredo Huete, Principal Investigator, and Kamel Didan, University of Arizona. Image accessed June 2008 at: http://visibleearth.nasa.gov/view_rec.php?id=2183.

C.   CLIMATE VARIABILITY IN TROPICAL WEST AFRICA

1.   Long-Term Mean Climate

The majority of rainfall in TWA is associated with the African summer monsoon and falls in the months of July, August, and September, with August receiving the maximum amount of annual rainfall (Nicholson 1979). Rainfall over TWA is generally associated with mesoscale convective systems (MCSs) that occur primarily ahead of the trough of African easterly waves (AEWs; Mekonnen et al., 2006). AEWs are dynamically modulated by the strength and position (instability) of the Tropical Easterly Jet (TEJ) and the African Easterly Jet (AEJ; Burpee 1972). The low-level Southwesterly Monsoon Jet (SWMJ) contributes moisture from the Atlantic Ocean to the growth and/or maintenance of the MCSs (Grodsky et al., 2003). In the Northern Hemisphere (NH) summer (July-August-September or JAS), the TEJ mean atmospheric level is between 200 and 150 hPa and the mean position over TWA lies at approximately 5°N. During the same time, the mean atmospheric level of the AEJ is 600 hPa and the mean position over TWA lies at approximately 12 to 15°N. The speeds and positions of the TEJ and AEJ are shown in Figure 3.
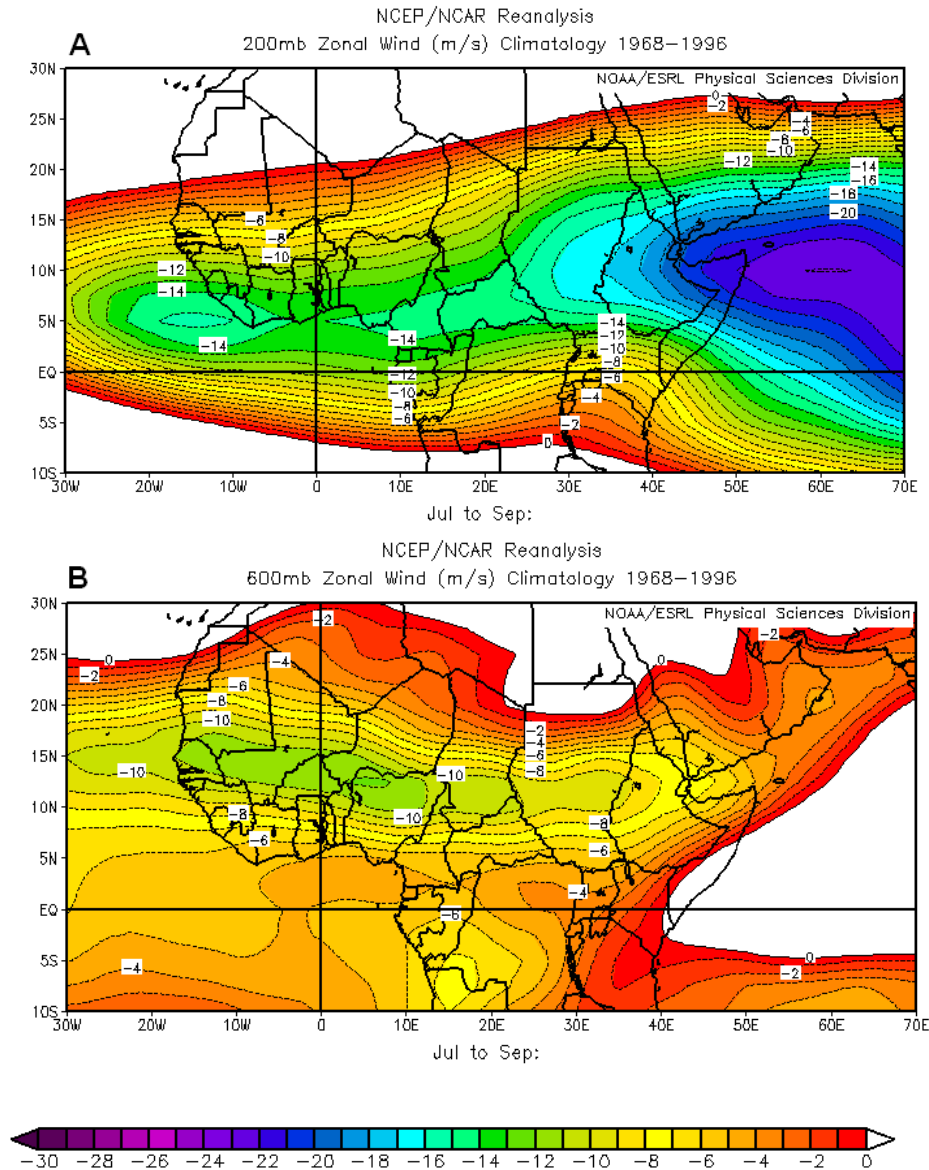
Figure 3.   Long-term mean speeds and locations of (A) the Tropical Easterly Jet (TEJ) at 200 hPa and (B) the African Easterly Jet (AEJ) at 600 hPa over Africa in July-August-September (JAS). Based on NCEP/NCAR reanalysis data for the long-term mean base period of 1968-1996.

2.   Observational Records for Analyzing Climate Variations in TWA Rainfall

Most of the research on the interannual or decadal variability of TWA rainfall has relied on observational rainfall records that span from the early 1900s

to the late 1900s. However, rainfall records in TWA are sparse, both spatially and temporally. Nicholson (1979) attempted to address this scarcity by developing a normalized annual rainfall departure data set for 1901-1975. This departure time series was divided into three regions, which Nicholson named Sahelo-Saharan, Sahel, and Soudan. The divisions between the regions were based on similarities in mean annual rainfall between individual reporting stations — in particular, the tendency for zonally oriented rainfall patterns in TWA. The rainfall departure was calculated by subtracting the long-term mean seasonal value from the seasonal mean value for each year and dividing by the standard deviation based on the full time series. The rainfall records used in these studies include 1901-2003 (years up to 2003 were included in Nicholson 2008a).

3. Climate Variations in TWA Rainfall

A number of studies have identified large variations in TWA rainfall occurring at intraseasonal to interdecadal scales. While the focus of this research is interannual variability, it is helpful to briefly review additional low frequency variability that may be influence TWA rainfall. Fontaine and Janicot (1996) described an interdecadal downward trend in summer Sahel rainfall during 1950-90, with the majority of wet Sahel summers occurring prior to 1970 and the majority of dry Sahel summers occurring after 1970. Several studies (e.g.,, Nicholson and Webster 2007) identified a large decrease in Sahel rainfall centered around the late 1960s. Nicholson and Webster (2007) labeled this decrease as "one of the most dramatic recent cases of abrupt climate change (that has) occurred in the West African Sahel." Baines and Folland (2007) associated this decrease with an abrupt shift in global atmospheric circulation and climate centered on the late 1960s. They cited a reduction in the northward oceanic heat flux associated with the North Atlantic thermohaline circulation as a likely candidate for this change.

Nicholson (1981) identified four primary patterns of interannual rainfall climate variability in TWA (Figure 4). These were: (1) a positive rainfall anomaly

in both the Sahel and Guinea coast regions (+/+); (2) a negative rainfall anomaly in both the Sahel and Guinea coast (-/-); (3) a positive rainfall anomaly in the Sahel and a negative anomaly in the Guinea coast (+/-); and (4) a negative rainfall anomaly in the Sahel and a positive anomaly in the Guinea coast (-/+). Nicholson (1981) identified the line of discontinuity for the dipole patterns as occurring at about 10°N, and this has been confirmed by subsequent studies (cf. Janicot 1992; Nicholson 1993).
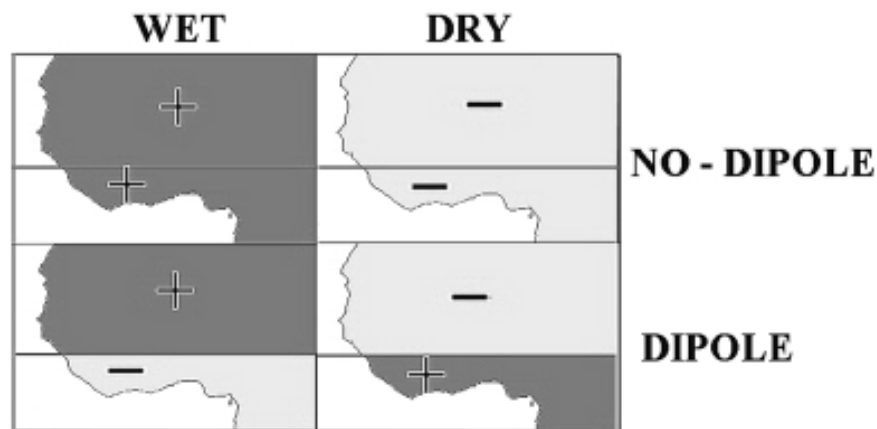
Figure 4.   Schematic illustration of the four most common rainfall anomaly patterns over West Africa. Light shading and – sign indicate below normal rainfall; dark shading and + sign indicate above normal rainfall. From Nicholson (2008a).

4.   Factors Affecting Interannual Variability

a.   *Position and Intensity of Tropical Rain Belt*

Nicholson and Webster (2007) proposed that the dynamic factors most important in determining the spatial mode of rainfall variability over TWA were the location and intensity of, primarily, the AEJ and secondarily, the location and intensity of the TEJ and the low-level SWMJ. They proposed that: (1) the AEJ, TEJ, and SWMJ interact dynamically to modulate the position and intensity of the tropical rain belt (TRB) in TWA – a zonally oriented region of vertical ascent and deep convection bounded by the TEJ and AEJ.   Differing

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combinations of the positions and intensities of the AEJ, TEJ, and SWMJ lead to the four anomaly patterns shown in Figure 4.

b.   Atlantic SST Anomalies

Fontaine and Janicot (1996) identified a positive simultaneous correlation between -/- rainfall anomalies in TWA and: (a) positive SST anomalies in the tropical eastern Pacific and Indian ocean basins; and (b) negative SST anomalies in the North Atlantic and the Gulf of Guinea. They also identified a positive simultaneous correlation between +/+ rainfall anomalies in TWA and positive SST anomalies in the North Atlantic.

c.   El Niño/La Niña (ENLN)

Janicot et al., (1996) concluded that the relationship between TWA rainfall and ENLN was strengthened after 1970, with positive (negative) SST anomalies in the eastern tropical Pacific (Atlantic) correlating to rainfall deficits over the whole of West Africa. Ward (1998) examined global scale teleconnections to TWA rainfall. A teleconnection is defined as a linkage between weather changes occurring in widely separated regions of the globe (Glickman (2000), accessed at: http://amsglossary.allenpress.com/glossary June 2008). Ward subdivided the years between 1904 and 1994 into dipole and non-dipole years (based on the TWA anomaly patterns presented in Figure 4). For the non-dipole years (of interest in this study), Ward documented an SST pattern that was well correlated to what he termed El Nino – Southern Oscillation (ENSO) and further, Ward specifically called attention to a positive correlation between the -/- mode, El Niño, and higher sea level pressure (SLP) in the tropical North Atlantic and equatorial West Pacific. Ward speculated that an ENSO connection with the non-dipole years (-/- and +/+) might occur via the Indian Ocean, as well as via modulation of Atlantic SSTs. Janicot et al., (1998) used a global atmospheric circulation model to explore connections between TWA and global SST anomalies for the years 1970-88. They found that positive SST

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anomalies in the eastern equatorial Pacific, fitting the pattern of El Niño warm events, coincided with negative rainfall anomalies over TWA. Conversely, they found that positive (warm) SST anomalies in the eastern equatorial Atlantic coincided with negative rainfall anomalies in the Sahel and positive anomalies along the Guinea coast.

d.   Equatorial Rossby-Kelvin Waves

Anomalous atmospheric convection accompanying EN or LN in the tropical Pacific often leads to anomalous atmospheric circulations in the Tropics and extratropics (Ford, 2000). The anomalous convection often forces an anomalous equatorially trapped Rossby-Kelvin (R-K) wave response (Matsuno 1966; Gill 1980; Figure 5).
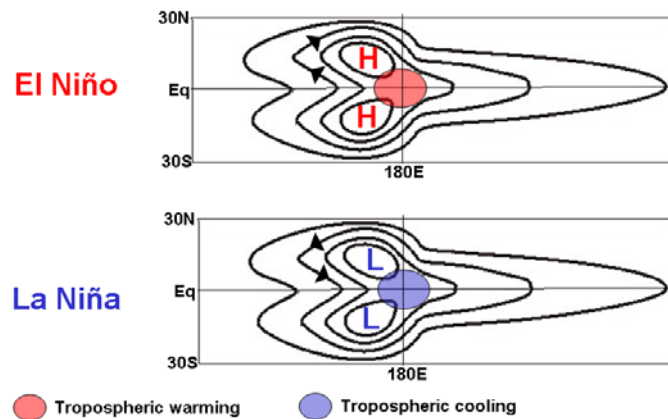
Figure 5.   Schematic upper tropospheric anomalies in response to anomalous (a) warming and (b) cooling of a tropospheric column centered on the equator. Contours show perturbation pressure isobars. There is a ridge in (a) and a trough in (b) at the equator and to the east of the forcing region. Note that the pressure to the west of the forcing region is different relative to its value off the equator. Note the paired (a) anticyclones and (b) cyclones to the northwest and southwest of the forcing region. From Ford (2000) and Tournay (2008).

Matthews (2004) used outgoing long-wave radiation (OLR) data to conclude that TWA intraseasonal variability was associated with the equatorial Rossby-Kelvin (R-K) wave response to Madden-Julian Oscillation (MJO) activity in the western Pacific. Matthews determined that the MJO activity in the western tropical pacific was capable of generating an eastward propagating Kelvin wave and a westward propagating Rossby wave that intersected over the tropical Atlantic-Africa region. Matthews suggested that this intersection increased instability and moisture transport into TWA, enhancing off-equatorial convective activity over the region. Matthews (2004) also speculated that similar equatorial wave activity occurring at interannual scales in association with ENLN events may also influence TWA rainfall.

e.   *Southern Hemisphere Rossby Wave Trains*

Karoly (1989) used analyses from the World Meteorological Centre in Melbourne, Australia to investigate the Southern Hemisphere (SH) low frequency wave response to EN events during 1972-1983. Karoly found that SH winter (JJA) circulation anomalies associated with EN events included an equivalent barotropic Rossby wave train that extended poleward and eastward over the SH Pacific and Atlantic basins (Figure 6). Rosencrans (2006) investigated intraseasonal variations in SH circulation anomalies and described an anomalous arching Rossby wave train originating from a cyclonic circulation anomaly in the tropical Pacific and extending into the tropical Atlantic region. The establishment of the cyclonic anomaly was shown to precede an increase in West African monsoon convection by two days.
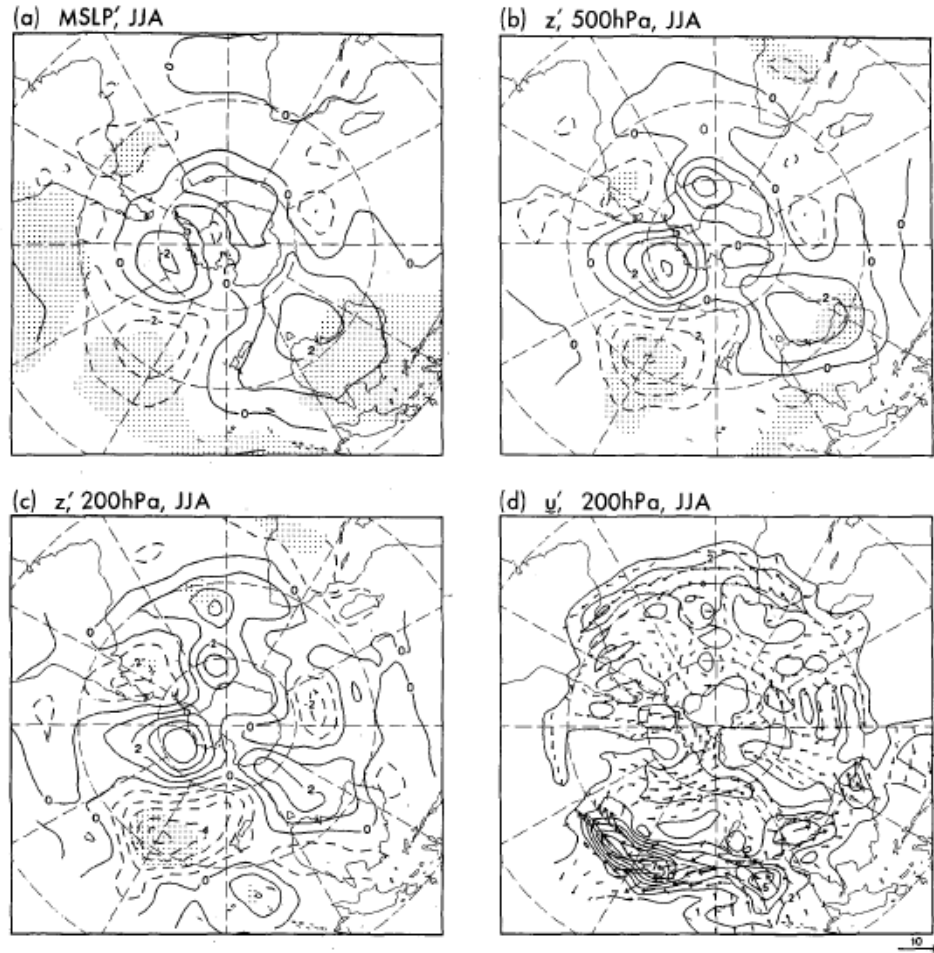
Figure 6.   Composite SH winter (June-July-August) anomalies for three EN events for (a) mean sea level pressure (hPa), (b) 500 hPa height (dam), (c) 200 hPa height (dam) and (d) 200 hPa wind (m s-1). Negative contours are dashed. In (a), (b) and (c), anomalies which are significant at the 95% level using a pointwise multiple permutation test have been shaded. From Karoly (1989).

D.   CLIMATE ANALYSES CONDUCTED IN THIS STUDY

The research in this study was conducted to investigate the global and regional changes in the atmosphere affecting the large-scale environmental factors that directly influence rainfall in tropical West Africa — in particular, the positions and intensities of the TEJ, AEJ and the SWMJ.   Figure 7 illustrates our overall approach to this research.
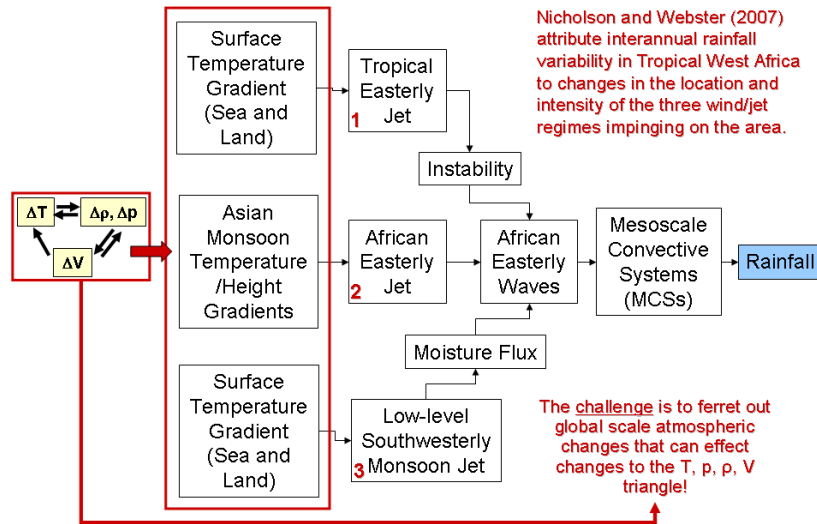
Figure 7.   A flow diagram for investigating relationships between TWA rainfall and large-scale environmental factors associated with air temperature (T), density (ρ), pressure (p), and wind (V).

Previous research (as outlined above) has failed to adequately address the relationship beween TWA rainfall and El Niño/La Niña (ENLN), and regional scale climate variations, specifically, sea surface temperature (SST) variations in the African portion of the Atlantic basin. Many have drawn correlations between specific ENLN regions in the Pacific and one, or occasionally two, of the anomalous rainfall classification modes for TWA (e.g., Janicot et al., 1996; Ward 1998). But these results are problematic, because the periods for which the correlations were made generally span the climate shift in the late 1960s. It is our opinion that previous research has missed the strong ENLN correlation to interannual variability in TWA rainfall because the paradigm has been to consistently consider years prior to 1970 in the exploration of global teleconnections.   When we included the pre-1970 JAS PRATE time series for the Sahel and Guinea coast regions in our composite analysis, we found that the correlations to ENLN decreased (cf. Janicot 1996).

Futher, the interaction between the three wind regimes over West Africa is still largely unquantified. Nicholson and Webster (2007) have made significant progress in relating anomaly patterns in the three wind regimes to the modes of

anomalous rainfall classification in TWA. The timescale used by Nicholson and Webster, similar to other research, spans the climate shift in the late 1960s. It was important for us to verify the relationships between anomalous TWA rainfall and anomalous zonal wind patterns for the most recent decades and after the climate shift of the late 1960s.

Most prior studies relied on rain gauge or other station data, and did not take advantage of the relatively high quality, and up to date, precipitation data sets based on satellite data and reanalysis methods. The study periods for prior studies on TWA rainfall do not include most or any of the years since 2000, when significant climate variations have occurred and for which relatively high quality precipitation data is available. For our study, we chose to take advantage of these newer data sets and additional years of data.

E.   PROJECTIONS OF FUTURE CLIMATE

1.   Intergovernmental Panel on Climate Change (IPCC) – Fourth Assessment Report (FAR)

The African chapter of the Intergovernmental Panel on Climate Change – Fourth Assessment Report (IPCC–FAR; Boko et al., 2007) concluded from climate modeling experiments that surface temperatures in northern Africa are likely to rise between 4 and 9°C (7.2 and 16.2°F) above their present levels by 2070-2099. Future precipitation estimates were noted as being "less reliable" due to the complexity of atmospheric and land surface dynamics that contribute to the location and intensity of rainfall, especially in TWA. However, model projections out to 2070-2099 indicated an approximate 20% decrease in mean annual rainfall for the northern African coast and southern border of the Sahara, but an approximate 7% increase in mean annual rainfall for tropical and eastern Africa. Additionally, the FAR indicated that the Sahel region (equivalent to or greater in extent to the combined Sahel and Guinea coast regions shown in

Figure 1) may experience a greater number of extremely wet or extremely dry rainfall years during the rest of the 21st century — an indication of increased interannual variability.

F.   CURRENT CLIMATOLOGICAL SUPPORT FOR TWA

1.   Department of Defense Operational Climatology Organizations

In 1943, the U.S. Air Weather Service published Technical Report 105-50, "The Meteorology of Central Africa: Accra, the Gold Coast and British West Africa" (Solot 1943). This publication was motivated in large part by U.S. and allied operations in this region as part of World War II. Over 60 years later, the Department of Defense (DoD) finds itself actively engaged in this region and elsewhere in Africa. Unfortunately, the level of awareness in DoD of the weather and climate of this region is only slightly higher than it was in 1943. Civilian research and operational efforts over the last several decades have greatly improved the understanding of meteorological, oceanographic, and climate patterns and processes in western Africa. However, most of this improved understanding has yet to be incorporated into the climatological support provided by DoD for military operations in this region.

Examples of DoD climate support products are shown in Figures 7-8. These figures are from a package of climate materials provided to a Naval Meteorology and Oceanography Mobile Environmental Team (MET) that deployed to the Gulf of Guinea in early 2008 in USS *Fort McHenry* (LSD 43) in support of the Naval European Command's African Partnership Station (APS). Prior to deploying to the Gulf of Guinea, a widely varied and diverse meteorological and oceanographic region, this team received information on long-term mean (LTM) conditions in the region from the U.S. Navy Fleet Numerical Meteorology and Oceanography Detachment (FNMOD), including the products shown in Figures 8-9.

Marine Climatological Overview
Global Marine Climatic Atlas 2.0

Gulf of Guinea

	Oct	Nov	Dec
Average Air Temp (°F)	79	81	82
Extreme Max/Min (°F)	90/68	90/70	90/72
Average Sea Temp (°F)	80	82	82
Winds (kts)	SW/09	S/08	S/07
Average Wave Height (ft)	3-5	2-4	2-4
Average Waves Direction (°)	200	180	180

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Marine Climatological Overview
Global Marine Climatic Atlas 2.0

Gulf of Guinea

	Jan	Feb	Mar	Apr
Average Air Temp (°F)	82	82	83	83
Extreme Max/Min (°F)	90/73	91/74	94/74	93/72
Average Sea Temp (°F)	82	83	84	84
Winds (kts)	SW/07	SW/07	SW/08	S/08
Average Wave Height (ft)	2-4	2-4	2-4	2-4
Average Waves Direction (°)	180	180	200	180

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Figure 8.   Examples of long-term mean climate information supplied to the USS *Fort McHenry* MET by FNMOD.
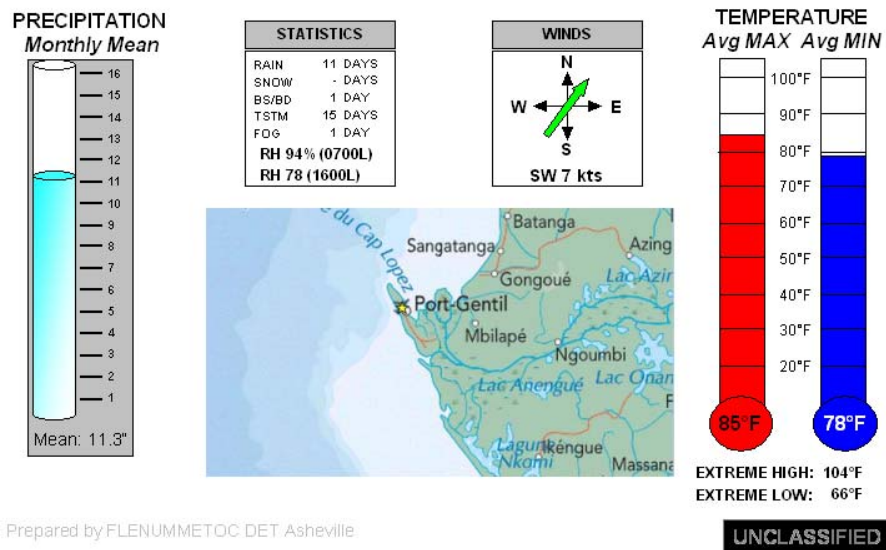
Figure 9.   Example of port-specific climate information supplied to the USS *Fort McHenry* MET by FNMOD.

The type of climate information provided by FNMOD and other DoD climate support centers is useful information regarding some aspects of climate in the Gulf of Guinea, especially long-term mean patters. However, it does very little to inform users of many important climate patterns and processes, or of operationally relevant tools for monitoring and predicting climate. For example, the FNMOD products provided to the *Fort McHenry* did not address West African monsoon patterns, atmospheric and oceanic conditions above or below the surface level, climate variations, or methods for climate analysis and forecasting in the region.

The 14th Weather Squadron, formerly the Air Force Combat Climatology Center (AFCCC), maintains a library of Technical Notes and Regional Studies on western Africa that is adequate to support an understanding of the LTM atmospheric conditions. In addition to the Technical Report mentioned above (from 1945), there are approximately 19 others covering 15 nations of the UN subregion of West Africa. The notes, reports, and studies published before 2005

generally describe only the LTM weather for the country or region of interest. Only in the most recent publications is there discussion of variations from the LTM patterns, such as those induced by ENLN, and these discussions are very brief and unlikely to be of much operational significance (e.g., Higdon 2007).

2. Civilian Operational Climatology Organizations

The African Desk at the Climate Prediction Center of the U.S. National Oceanic and Atmospheric Administration (NOAA) has a responsibility to "focus on short term climate monitoring and prediction for Africa" (from http://www.cpc.ncep.noaa.gov/products/african_desk/, accessed May 13, 2008). The African Desk has shown admirable initiative in the development of a seasonal and weekly outlook on African weather. The seasonal outlooks are statistical forecasts based canonical correlation analysis (CCA). For the outlooks found on the African Desk website, the analysts use "quasi-global" SSTs between 40°S and 60°N on a 10° X 10° grid to predict rainfall over Africa. The African Desk works closely with the Famine Early Warning System Network (FEWS NET) to produce weekly and seasonal outlooks that FEWS NET can then incorporate into forecasts for food security. There is currently no information posted regarding the verification of the CPC climate forecasts, however, the seasonal lead times provided in the forecast range could be beneficial to DoD operational planners.

Other civilian operational climatology organizations also provide analysis and prediction products for Africa, including the International research Institute for Climate and Society, Earth Systems research Laboratory, and Australian Bureau of Meteorology. Vorhees (2006) and Tournay (2008) provide overviews of these organizations.

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II.   OVERVIEW OF THE REGIONAL STABILITY OF THE GUINEA COAST

A.   CULTURE OF TROPICAL WEST AFRICA

1.   History, Geographic Boundaries, and Statehood

Most national boundaries in TWA follow the old boundaries established by the European colonial powers. Many of the current nations in TWA were not long ago under colonial rule by the United Kingdom, France, or Portugal. Of the 16 nations comprising the United Nations subregion of West Africa, only one nation, Liberia, has been an independent state for more than 50 years. The other 15 nations declared independence from their colonial powers from 1957 (the earliest) to 1975 (the latest) with the majority of declarations occurring in 1960. In the decades prior to colonial rule, West Africa saw the rise and fall of several tribal kingdoms and empires.

Prior to and during colonial rule, many West African social groups were converted from traditional indigenous (mostly animist) religions to Christianity and Islam. The U.S. (DoS) Report on International Religious Freedom (2007) indicates that in almost all West African nations, the percentage of the population in each nation that considers itself Muslim is on the rise. The summary of the religious orientation of the population of all UN West Africa subregion nations is shown in Figure 10. Over 50% of the population in West Africa is Muslim and the majority of the Muslim population in West Africa is of the Sunni branch of Islam. Hanford (2007) indicates that in much of West Africa, internal conflict are occurring more and more along religious lines.

Religious Affliations in West African Nations

Muslim
54%

Christian
29%

Other/None
1%

Traditional
Indigenous
16%
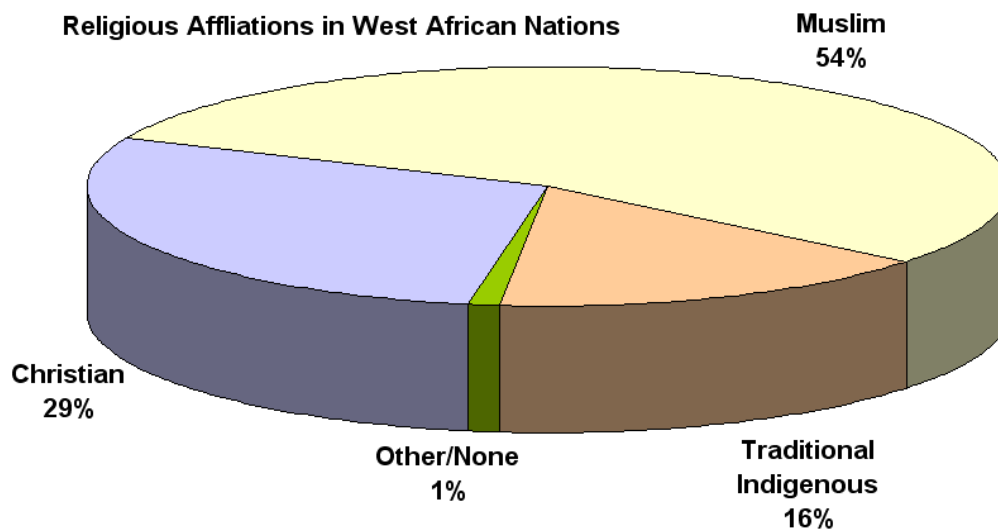
Figure 10.   Major religious affiliations for the UN subregion of West Africa.
Summarized from the US Department of State – Bureau of Democracy, Human
Rights and Labor: International Religious Freedom Report (2007)
(http://www.state.gov/g/drl/rls/irf/2007/) accessed May 2008.

2.   Livelihoods

The Famine Early Warning System Network (FEWS NET) is an
organization funded by the US Agency for International Development that is
developing livelihood assessments for Burkina Faso, Chad, Mali, Mauritania,
Niger, and Nigeria. These Sahelian countries frequently have to contend with
food shortages. The livelihood assessments are based on household economy
analyses based on first hand accounts of how populations secure food and
income   (from   http://www.fews.net/ml/en/info/Pages/liveprodmeth.aspx?l=en,
accessed June 2008). The majority of the rural population – accounting for 70%
or more of total national population - in the nations of western Africa can be
grouped into three livelihood categories; (1) pastoral nomads, (2) coastal fishers,
or (3) agro-pastoralists. Pastoral nomads and agro-pastoralists depend heavily
on rainfall for their livelihoods. So interannual variations in of TWA rainfall are
especially important to them. In particular, -/- events, in which rainfall is low in
both the Sahel and Guinea coast regions (see Chapter I, Section C.3), are

especially important, since during these events dry conditions are very extensive and the option of migrating to wetter regions becomes less viable. Low TWA rainfall is especially critical during June and July (sometimes referred to as the hunger gap months). These months mark the beginning of the rainy period, and low rainfall at this time amounts to an extension of the less productive dry season when milk production is low and agricultural stores are depleted (from Livelihood Profiles accessed at: http://www.fews.net/Pages/livehome.aspx, June 2008).

The impacts of rainfall and other factors on the availability of food are often described in terms of food security. The Food and Agriculture Organization (FAO) defines food security as existing when all people, at all times, have access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life (Thomson and Metz 1997). Various other organizations throughout history have created their own definition for the lack of food security, or food insecurity — definitions that have often been modified for political reasons to support or deny cases of famine in third world countries. Howe and Devereux (2004) were the first to formalize a classification scheme for famine based on intensity and magnitude. Their scheme is shown in Tables 1 and 2.

Table 1. Intensity scale for famine. From Howe and Devereux (2004).

Levels	Phrase designation	'Lives': malnutrition and mortality indicators	'Livelihoods': food-security descriptors[16]
0	Food-security conditions	CMR < 0.2/10,000/day and Wasting < 2.3%	Social system is cohesive; prices are stable; negligible adoption of coping strategies.
1	Food-insecurity conditions	CMR >= 0.2 but < .5/10,000/day and/or Wasting >=2.3 but < 10%	Social system remains cohesive; price instability, and seasonal shortage of key items; reversible 'adaptive strategies' are employed.
2	Food crisis conditions	CMR >=.5 but < 1/10,000/day and/or Wasting > =10 but < 20% and/or prevalence of Oedema	Social system significantly stressed but remains largely cohesive; dramatic rise in price of food and other basic items; adaptive mechanisms start to fail; increase in irreversible coping strategies.
3	Famine conditions	CMR >=1 but < 5/10,000/day and/or Wasting > =20% but < 40% and/or prevalence of Oedema	Clear signs of social breakdown appear; markets begin to close or collapse; coping strategies are exhausted and survival strategies are adopted; affected population identify food as the dominant problem in the onset of the crisis.
4	Severe famine conditions	CMR >5= but <15/10,000/day and/or Wasting > = 40% and/or prevalence of Oedema	Widespread social breakdown; markets are closed or inaccessible to affected population; survival strategies are widespread; affected population identify food as the dominant problem in the onset of this crisis.
5	Extreme famine conditions	CMR > =15/10,000/day	Complete social breakdown; widespread mortality; affected population identify food as the dominant problem in the onset of the crisis.

CMR: crude mortality rate.
Wasting: proportion of child population (six months to five years old) who are below 80 per cent of the median weight-for-height or below –2 Z-score weight-for-height (cf. NCHS, 1977).

Table 2. Magnitude scale for famine. From Howe and Devereux (2004).

Category	Phrase designation	Mortality range
A	Minor famine	0–999
B	Moderate famine	1,000–9,999
C	Major famine	10,000–99,999
D	Great famine	100,000–999,999
E	Catastrophic famine	1,000,000 and over

Additionally, even minor changes in growing conditions in the Sahel have major implications for people's food security and nutrition. There are already extremely high levels of malnutrition in the Sahel, even in years when rainfall is adequate, with children under five bearing the brunt of hunger and disease (UN Office for the Coordination of Humanitarian Affairs (OCHA) 2008). FEWS NET publishes quarterly forecasts of food security for many of the nations in West Africa. The outlook for July, August, and September of 2008 is shown in Figure 11.
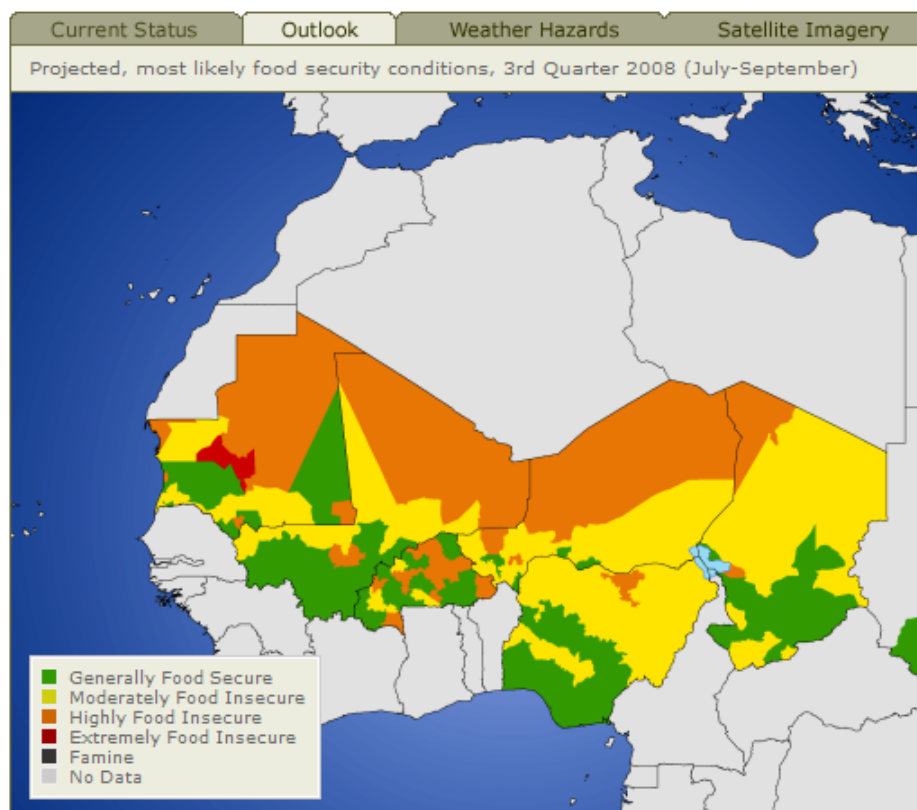
Figure 11.   July, August, and September 2008 outlook for food security conditions in West Africa courtesy of FEWS NET. Accessed June 2008 at: http://www.fews.net/Pages/region.aspx?gb=r1&l=en .

3.   Social and Economic Stresses Imposed by Climate Variability

Thomson and Metz (1997) examined the sources of risk to food security using the concept of entitlements. Sen (1981) defined entitlements as "the set of alternative commodity bundles that a person can command in a society using the totality of rights and opportunities that he or she faces". Entitlements can be classified as: (1) trade-based, (2) production-based, (3) labor-based, or (4) inheritance- or transfer-based. Loss of entitlement, or "entitlement failure suffered by a large section of the population" (Dreze and Sen 1990a) has been proposed as a cause of famine. Dreze and Sen (1990a) suggested that short-term, emergency entitlement protection could be a way of averting immediate famine in Africa, but that long-term famine prevention and stability could only be achieved by building flexible and effective response mechanisms for entitlement protection. The sources of risk to food security identified by Thomson and Metz (1998) based on the entitlement concept are shown in Table 3.

Table 3.   Sources of risk to household food security (After Thomson and Metz (1997).

Sources of Entitlement	Types of Risk				
	Natural	State	Market	Community	Conflict
Productive Capital (land, machinery, tools, animals, farm buildings, trees, wells, etc.)	Drought, Contamination (e.g. of water supplies), Land Degradation, Fire, Flooding	Land of other, Asset Redistribution/Confiscation	Changes in Costs of Maintenance	Appropriation and Loss of Access to Common Property Resources	Loss of Land as a Result of Conflict
Non-productive Capital (jewellery, dwellings, granaries, some animals, cash savings)	Pests, Animal Disease	Compulsory Procurement, Villageisation, Wealth Tax	Price Shocks (e.g. falls in value of jewellery or livestock), Rapid Inflation	Breakdown of Sharing Mechanisms (e.g. communal granaries)	Loss fo Assets as a Result of War, Theft
Human Capital (labour power, education, health)	Disease, Epidemics (e.g. AIDS), Morbidity, Mortality, Disability	Declining Public Health Expenditure, Introduction of User Charges, Restrictions on Labour Migration	Unemployment, Falling Real Wages	Breakdown of Labour Reciprocity	Forced Labour Conscription, Mobility Restrictions, Destruction of Schools and Clinics During War
Income (crops, livestock, non-farm and non-agricultural activity)	Pests, Drought and other Climatic Events	Cessation of Extension Services, Subsidies on Inputs or Price Support Schemes, Tax Increases	Commodity of Extension Services, Subsidies on Inputs or Price Support Schemes, Tax Increases		Marketing Channels Disrupted by War, Embargoes
Claims (loans, gifts, social contacts, social security)		Reduction in Nutrition Programmes (e.g. school supplementary feeding)	Rises in Interest Rates, Changes in Borrowing Capacity	Loan Recall, Breakdown of Reciprocity	Communities Disrupted/Displaced by War.

Note that the column labeled "Natural" in Table 3 includes climate related risks to entitlements, but that climate related risks are not the only risks to population entitlements and food security. All of the risks outlined in Table 3 have been, and are now being, imposed upon populations in TWA. No specific risk factor has, or combination of risk factors have, been demonstrated to lead to

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food insecurity or famine. In most cases, humanitarian crises result from non-linear interactions and feedback cycles between risk factors.

4.   Drought in Western Sahel

The Sahel is a marginal environment for two of the three livelihoods supporting economic production, the pastoral nomad and agro-pastoralist livelihoods (cf. FEWS NET 2005). Thus, in the Sahel, the balance between subsistence and crisis is delicate and very sensitive to climate variability. The two most recent drought and famine events in western and eastern Africa occurred during 1968-1973 and 1984-1985. These two periods coincide with lengthy (> 1 year) periods of significant decreases in JAS precipitation rate. The first period occurred just after the abrupt climate shift in the late 1960s when a large decrease in Sahel rainfall occurred (see Chapter I, Section C.3 and Chapter V, Section A.1). The second period occurred after three consecutive years of below mean JAS precipitation rate in the early 1980s. Most of TWA experienced famine during these two periods (Dreze and Sen 1990b). However, some managed to avoid famine during these periods – Cape Verde even experienced improvement in living conditions (Dreze and Sen 1990b). Drought in TWA significantly raises the risk of famine but does not guarantee that famine will occur. Dr. Jan Egeland, the UN Secretary General's Special Advisor on Conflict, during a recent trip to the Sahel remarked, "…this trip has convinced me that there is a very clear link between climate induced resource competition and conflict" (Egeland 2008).

III. WHY SHOULD MILITARY PLANNERS CARE?

A. DEPARTMENT OF DEFENSE PLANNING

The Joint Planning, Programming, Budgeting and Execution (PPBE) process is designed to develop the Department of Defense portion of the President's budget request to Congress (Otte 2008). The process occurs over two years. In even-numbered fiscal years (FY), the Program Objective Memorandum (POM) is packaged in a Budget Estimate Submission (BES) provided to the President. In odd-numbered fiscal years, programs are reviewed (Program Review – PR) and changes are submitted via the Budget Change Proposal.

In the PPBE process, resource and program timelines are considered for the even numbered FY budget under construction, the odd numbered FY of program review and the following four years (the out years). For each year, a Future Year Defense Plan (FYDP) is developed. For example, in calendar year 2008, the FY 2008 budget is executed, and the Joint Programming Guidance (JPG) for the 2010 budget (POM-10) is issued. The 2010 budget, or POM 10 will include a FYDP for 2010 and 2011 – the even-numbered fiscal year and the odd-numbered review year, respectively – plus four fiscal out years, 2012-2015. Otte (2008) noted that in the Joint PPBE Process, "… major program development and acquisition are extended processes, [and] there are significant force implications beyond the FYDP out-years" (Figure 12).

The diagram shows a series of overlapping file folder tabs arranged diagonally:

- FY - 15
- FY - 14
- FY - 13
- FY - 12
- **FYDP Out - Years**
- FY - 11
- FY - 10
- **FYDP Budget Years**
- FY - 09
- **Congressional Budget**
- FY - 08
- **Current Execution**

FYDP – Database containing DoD resources and programs approved by **SECDEF** for a particular **PPBE** cycle; considered internal DoD working document, although submitted to Congressional oversight committees

Budget development incorporates all PPBE phases with ultimate goal of executable programs throughout the Future Year Defense Plan

Figure 12.   Pictorial representation of the timeline for the PPBE process. From Otte (2008).

In the case of TWA, the "major program development and acquisition" likely to impact the operational capacity of the DoD on a regional scale is the Global Fleet Station, and on a continental scale, the US Africa Command (AFRICOM). Adherence to the PPBE process means that decisions regarding capabilities, logistics, and force structure of the Global Fleet Station or AFRICOM are made on the order of seven years in advance (e.g., in 2008 for 2015). Thus, significant amounts of DoD planning occur at long lead times. For such interannual to decadal periods, significant variations can occur in the physical environment in which DoD operates. Thus, DoD plans should account for established capabilities in operational climatology --- in particular, the ability to analyze, monitor, and predict climate variations (e.g., ENLN, MJO) and climate change (e.g., long term trends associated with global warming) in regions of DoD interest (e.g., TWA).

B.   WAR-GAMING AND THE ENVIRONMENT

Joint Publication 3-59; *Joint Doctrine, Tactics, Techniques, and Procedures for Meteorological and Oceanographic Operations* (Joint Staff 1999) states:

> The integration of METOC [meteorology and oceanography] information into the planning process allows the JFC [Joint Forces Command] and subordinate joint forces to make informed decisions with regard to the design and operation of a plan and the use of various weapon systems.   Early integration of information from METOC studies developed from climatological databases can aid the long-range planning of military operations as well.

In June 2007, then Chief of Naval Operations (CNO), Admiral Mike Mullen, tasked the Naval War College (NWC) to

> help develop a new maritime strategy that will describe the way in which the nation's maritime forces will be structured and utilized to ensure security of the global maritime commons over the next decade.
> — (NWC website
> http://www.nwc.navy.mil/cnws/marstrat/default.aspx#, accessed May, 2008)
>
> —The NWC response to this tasking included an initial assessment of the geo-strategic environment (NWC website http://www.nwc.navy.mil/cnws/marstrat/docs/research/Aug_25_Geo strategic_Workshop_Final_Report.pdf, accessed May 20, 2008).

This assessment was conducted by analyzing a set of factors that are expected to affect "national security and the application of military power" over the next several decades.   The physical environment was one of the factors evaluated. A few key findings from this assessment include:

- Environmental issues will come even more to the fore [in the next several decades].

- The effects of global warming continue to increase.

- Global warming will generate both winners and losers as the climate changes. [The potential security implications of these wins and losses need to be evaluated.]

- Beneficial economic impacts of globalization will eventually mean beneficial environmental impacts as well.

- Poor land management and the overuse of fertilizers are causing land degradation, soil erosion, and desertification, and are taking place on a massive scale in agricultural areas from the Amazon to the Yangtze.

It is encouraging that NWS is conducting an assessment of the impacts of the changing physical environment on DoD planning and the crafting of a new maritime strategy. However, in-depth technical analyses are needed to sufficiently consider the implications of the changing environment on military strategy and operations. Broad-brush geo-strategic assessments can only be a starting point.

In late 2007, Congress added Section 931 to the 2008 National Defense Authorization Act (NDAA) requiring the Department of Defense to consider the implications of global climate change. The direction of the amendment is clear and far-reaching. The amendment reads (110th Congress 2008):

Section 118 of title 10, United States Code, is amended by adding at the end the following new subsection:

(g) Consideration of Effect of Climate Change on Department Facilities, Capabilities, and Missions-

(1) The first national security strategy and national defense strategy prepared after the date of the enactment of this subsection shall include guidance for military planners--

(A) to assess the risks of projected climate change to current and future missions of the armed forces;

(B) to update defense plans based on these assessments, including working with allies and partners to incorporate climate mitigation strategies, capacity building, and relevant research and development; and

(C) to develop the capabilities needed to reduce future impacts.

(2) The first quadrennial defense review prepared after the date of the enactment of this subsection shall also examine the capabilities of the armed forces to respond to the consequences of climate change, in particular, preparedness for natural disasters from extreme weather events and other missions the armed forces may be asked to support inside the United States and overseas.

(3) For planning purposes to comply with the requirements of this subsection, the Secretary of Defense shall use--

(A) the mid-range projections of the fourth assessment report of the Intergovernmental Panel on Climate Change;

(B) subsequent mid-range consensus climate projections if more recent information is available when the next national security strategy, national defense strategy, or quadrennial defense review, as the case may be, is conducted; and

(C) findings of appropriate and available estimations or studies of the anticipated strategic, social, political, and economic effects of global climate change and the implications of such effects on the national security of the United States.

(4) The Secretary shall ensure that this subsection is implemented in a manner that does not have a negative impact on national security.

(5) In this subsection, the term `national security strategy' means the annual national security strategy report of the President under section 108 of the National Security Act of 1947 (50 U.S.C. 404a).

The 2008 NDAA does not merely suggest that military planners consider the implications of climate change on DoD capabilities and missions, but *requires* the incorporation of climate research in mission risk assessment, defense planning, and the development of new capabilities needed to reduce future impacts.

C. THE NEW MARITIME STRATEGY

Admiral Mullen, along with the Commandants of the Marine Corps and Coast Guard, crafted a new maritime strategy in 2007; it was unique in that it placed an equal focus on fighting and winning wars and on maintaining peace. Admiral Gary Roughead, who relieved Mullen as CNO, emphasized this unique guidance in his commencement address to the Naval Postgraduate School graduating class in March 2008:

> The strategy is one that encompasses the sentiment that we can ensure peace today with an equal focus on preventing and winning wars. It's a goal that has the commitment of the Navy, the Marine Corps, and the Coast Guard. It's a goal that will require more than our enduring capabilities of just being a forward Navy, a deterrent Navy, being able to control the seas and being able to project power. It requires international partnerships and levels of cooperation and trust that are going to be so important in the worlds of tomorrow.

The need for this new type of maritime strategy is clearly demonstrated in TWA, where the DoD is engaged in a unique environment that calls for an emphasis on doctrinal phase 0, or shaping and stability operations, that have historically been led by the Department of State (DoS) or the US Agency for International Development (USAID). The US Navy is leading the other services in its attempt to define requirements and infrastructure needed to adequately act in a security and capability-building role via the Global Fleet Station (GFS) concept.

1. The Global Fleet Station Concept

In April 2008, US Fleet Forces Command released the promulgation message regarding the Global Fleet Station Concept of Operations (CONOPS). This CONOPS:

> …is focused around forward presence/seabasing missions that support the Combatant Commander's phase zero shaping operations and provides a level of understanding necessary to

assist Theater Security Cooperation (TSC) and naval component planning cells to determine the appropriate adaptive force packages to support assigned missions (CFFC 2008).

The promulgation message outlined achievement milestones required for the GFS concept to become fully operational. An operational GFS could be tasked to conduct foreign humanitarian assistance (FHA), humanitarian and civic assistance (HCA), civil-military operations (CMO), security cooperation (SC), and/or regional partner capacity building missions.

A significant shortcoming of the GFS CONOPS documents is that they do not clearly address the physical environment factors (e.g., climate variations) that contribute to the need for FHA, HCA, CMO, SC, and RPCB missions. For may regions in which these missions have or are likely to occur, such factors, are significant and should be accounted for in planning GFS operations.

2.   The African Partnership Station

One of the first tests of the GFS concept occurred in the Gulf of Guinea in 2008. The Gulf of Guinea GFS supported HCA, CMO, SC, and RPCB missions in many of the nations of TWA. This effort was led by the Naval European Command, and during this effort, the Gulf of Guinea GFS was renamed the African Partnership Station (APS). The APS concluded its first deployment on April 9, 2008 (APS 2008). The deployment began on October 30, 2007, when the USS *Fort McHenry* departed Naples, Italy and "visited 19 ports of call in 10 countries and trained over 1500 maritime professionals in skills ranging from small boat handling, port security, and martial arts to non-commissioned officer leadership, damage control, and maritime law" (APS 2008) The APS was a success in that it demonstrated the US Navy's capacity to conduct the missions included in the GFS CONOPS, in particular the SC mission. The success of this first APS will likely result in future GFS missions in the area as the need for FHA, HCA, CMO and SC are likely to exist in TWA for the foreseeable future. What is uncertain is the willingness and/or ability of the US Navy and DoD to address the

root causes of the instability in TWA and the continuous need for FHA, HCA, and CMO missions across the vast continent. The establishment of the United States Africa Command – the first Unified Combatant Command focused solely on the African continent – is a large step by DoD toward understanding how African success, conflict, poverty, instability, and security will impact the United States in an increasingly globalized world.

D.   UNITED STATES AFRICA COMMAND (AFRICOM)

In October 2007, the U.S. Africa Command reached initial operating capacity as a sub-unified command under U.S. European Command (EUCOM) at EUCOM headquarters in Stuttgart, Germany.   The creation of the new combatant command represents a change to the Unified Command Plan (UCP), one of the most significant changes since the terrorist attacks on the U.S. on September 11, 2001.
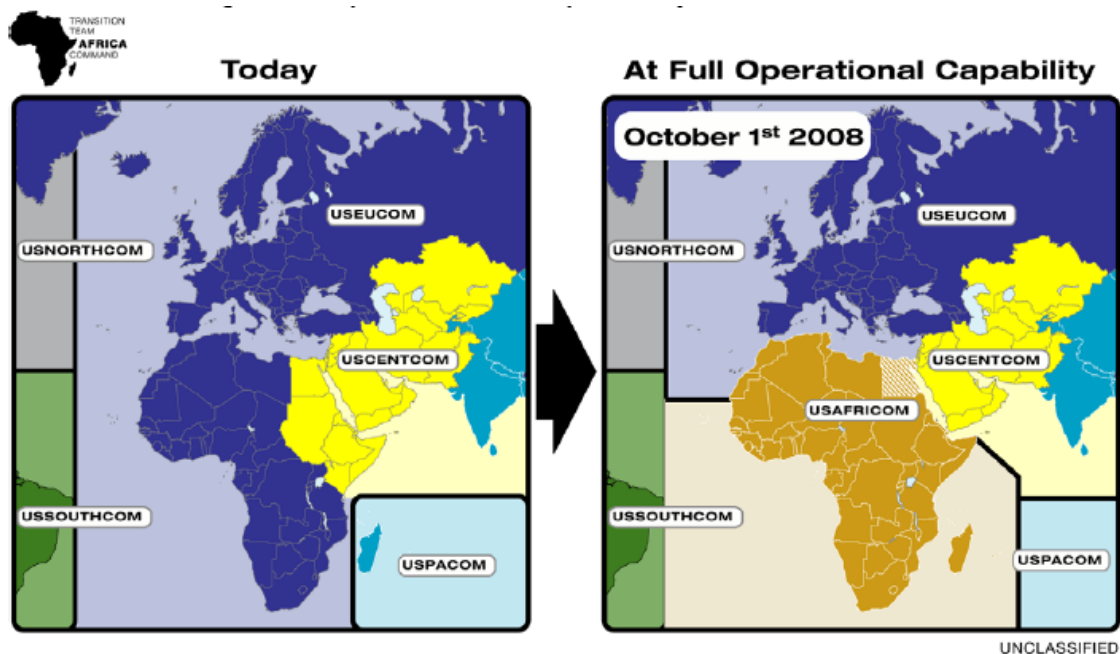
Figure 13.   Representation of the operational areas of responsibility for each regional combatant command in the Africa region in 2007 (left panel) and with the inclusion of AFRICOM in 2008 (right panel). From Ploch (2007).

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AFRICOM is designed to enable the DoD and other US government agencies to work together to achieve a more stable Africa with a focus on war prevention rather than war-fighting (http://www.africom.mil, accessed May 2008). AFRICOM plans to excel in the Phase 0 - shaping and stability mission using a unique command structure that incorporates other governmental agencies (OGAs) and non-governmental organizations (NGOs; e.g., World Food Program (WFP), Save the Children, etc.), including a DoS civilian, Ambassador Mary Yates, as deputy commander for civil-military activities. The proposed command structure is a drastic change from the structure of all previous and existing combatant commands. It may present as many challenges as it does opportunities for collaboration because, as spokesman for AFRICOM, Colonel Pat McMackin, stated, "There is no government mechanism for creating a truly interagency headquarters" (Lubold 2008).

There has been some opposition to the proposed roles and missions of US Africa Command. Opposition recently voiced by the House Armed Services Committee concerned the perception that AFRICOM would be "militarizing U.S. foreign policy by taking over responsibilities traditionally held by government agencies and other departments" (Skinner 2008 – AFRICOM PAO, http://www.africom.mil/getArticle.asp?art=1770 , accessed June, 2008). Admiral Moeller addressed the concern by stating, "There were some concerns expressed that perhaps what we were doing is kind of reaching in and looking to assume responsibility for U.S. foreign policy in Africa. That is absolutely not the case." (Skinner 2008).

However, if AFRICOM is to be successful, it must account for many of the physical environmental factors that affect Africa, including climate variations and climate change. To do so, it will need to partner with operational climatology organizations that have the capacity to analyze, monitor, and predict climate factors that affect African stability. These organizations are mainly civilian organizations (e.g., CPC, IRI) that have worked with DoS, OGAs, and NGOs in the past (see Chapter I, Section E). Presently and in the foreseeable future, DoD

operational climatology organizations are not capable of providing up-to-date long-term means, analyses, monitoring assessments, predictions, or projections (see Chapter I, Section E).

IV. DATA AND METHODS

A. DESCRIPTION OF CLIMATE DATA SETS

1. National Centers for Environmental Prediction / National Center for Atmospheric Research Reanalysis

Our primary source of data for this study was the National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data set, accessed via the Earth Systems Research Laboratory (ESRL) website at http://www.noaa.cdc.gov (last accessed 19 June 2008). NCEP and NCAR designed the reanalysis project to use a "frozen state-of-the-art global data assimilation system" to "produce a 40-year record of global analysis of atmospheric fields" (Kalnay et al., 1996). The data used to populate the (then) 40-year record of atmospheric fields was collected from a multitude of sources including; "land surface, ship, rawinsonde, pibal, aircraft, satellite, and other observational data" (Kalnay et al., 1996). The primary reanalysis fields used for this research were:

- Precipitation rate (PRATE)
- Geopotential height (GPH)
- Zonal wind (u)
- Meridional wind (v)
- Surface skin temperature (sea surface temperature (SST))
- Outgoing longwave radiation (OLR)
- Omega (vertical velocity, ω)

The main levels of interest for our study were 200, 600, 850, and 925 hPa and the surface. OLR was used as an indicator of deep tropical convection, with low values of OLR in the tropics corresponding to high, cold cloud tops overlying convective regions. Omega was used as an indicator of convection and

subsidence regions, with negative (positive) values throughout much of the troposphere indicating ascent and deep convection (descent and deep subsidence)

The reanalysis fields are available from 1948 to the present, at monthly, daily and 6-hourly timescales, at 2.5° horizontal resolution. We used the monthly fields from 1970-2007. We considered only these 38 years in order to focus our analyses on: (1) the climate patterns and processes that have occurred since the abrupt climate shift in TWA during the late 1960s (see Chapter 1, Section C); and (2) a period in which data was relatively abundant due to the advent of the satellite era (cf. Ford 2000; Tournay 2008).

Our investigation of teleconnections to TWA rainfall was focused on analyses of PRATE for the Sahel and Guinea coast regions (see Chapter I, Section B). These regions were chosen based on the spatially coherent PRATE variations identified in this study and in prior studies by Nicholson (1979), Janicot (1996), Ward (1998), and others. PRATE is a C variable in the NCEP/NCAR reanalysis, meaning that PRATE, "is derived solely from the model fields forced by the data assimilation to remain close to the atmosphere" (Kalnay et al., 1996). Despite the derived nature of the PRATE field, Janicot et al., (2001) and Matthews (2004) found the NCEP-NCAR reanalysis adequately captured the interannual variability of TWA.

B.   DESCRIPTION OF CLIMATE INDICES

1.   El Niño/La Niña

ENLN events are a major source of interannual variability in the tropics (e.g., Janicot et al., 2001). Many different methods are used for the classification and determination of the severity of these events. We chose to use the Multivariate ENSO Index (MEI) introduced by Wolter and Timlin (1993) for this study. The MEI is based on six observed variables over the tropical Pacific: SLP, surface zonal wind, surface meridional wind, SST, surface air temperature, and

total cloudiness fraction of the sky. The MEI value for each of twelve sliding bi-monthly seasons (e.g., Jan/Feb, Feb/Mar…Dec/Jan) dating back to 1950 can be found at http://www.cdc.noaa.gov/people/klaus.wolter/MEI/table.html (last accessed 19 June 2008).   For this study, the MEI was used for both statistical correlation and composite analyses.   The statistical correlations used the published values of MEI for each bimonthly period of interest. In the composite analyses, the threshold for a strong EN (LN) event was set at +1.0 (-1.0) for at least two of the bimonthly MEI values during a three month season (e.g., JAS). Thus, only the strongest EN and LN events were used for compositing.

C.   DESCRIPTION OF DATA ANALYSIS METHODS

1.   Time Series Development

Monthly time series of PRATE and other climate variables were created for the years 1948-2007 for the Sahel and Guinea coast regions. Our preliminary analyses of this time series confirmed that the maximum rainfall for these regions tends to occur in July, August, and September (JAS) consistent with the results from prior studies (e.g., Nicholson 1981, 2008). Much of our motivation for conducting this study was based on determining the relationships between TWA climate variations, stability, and long range DoD planning. Rainfall anomalies during JAS are a primary way in which climate variations influence stability in TWA (cf. Thompson and Metz 1998), and thus influence the need for DoD operations in TWA. Thus, for most of our analyses, we focused on JAS, the main months of the rainy season in TWA.

To facilitate the analyses of climate variations, we calculated time series of the normalized climate anomalies, or departures from the long-term mean (LTM), for each variable of interest. For example, for JAS PRATE in the Sahel and Guinea coast regions, the normalized anomaly was calculated as:

JAS PRATE anomaly =

[(JAS PRATE for year i region r)

*– (LTM JAS PRATE for region **r**)]*

÷ (JAS PRATE standard deviation for region **r**)

For the normalized anomaly time series, the LTM base period was the full study period, 1970-2007. For our spatial analyses of anomaly patterns and processes, and for our spatial correlation and teleconnection, we used several analysis tools provided online by ESRL. For these analyses, we used the ESRL base period, 1968-1996. In our initial research, we determined that there is very little difference between the two LTMs for the variables, locations, and periods of interest for this study. Our subsequent research indicated that our main results our insensitive to the choice of these two different base periods. Both base periods exclude the climate that occurred in the late 1960s (see Chapter I, Section C.3).

2.   Composite Anomaly Analyses

We used composite anomaly analyses to explore the regional and global patterns and dynamical processes related to the +/+ and -/- anomalous rainfall patterns in TWA (see Chapter I, Section C.3). These composite anomalies were calculated for each of the variables listed in Chapter IV, Section A.1. To compute these composite anomalies, we used the normalized PRATE anomaly time series for JAS to identify periods of extreme rainfall anomalies in the Sahel and Guinea coast regions. The periods with normalized PRATE anomalies greater than +0.5 (-0.5) were identified as strong positive (negative) rainfall anomaly periods. Periods for which strong positive (negative) rainfall anomalies existed in both regions were identified as non-dipole +/+ or wet (-/- or dry) periods (Table 4). The +/+ (-/-) composite anomalies were constructed by averaging together the anomalies for the +/+ (-/-) years shown in Table 4.

Table 4.   Years in which TWA JAS precipitation rate (PRATE) values for 1970-2007 indicated non-dipole +/+ conditions (left half of table) and -/- conditions (right half of table). The +/+ (-/-) periods correspond to anomalously high (low) rainfall in both the Sahel and Guinea coast regions of TWA. The normalized PRATE anomaly values for each year are also shown.

Non-dipole Years					
+/+			-/-		
	Anomaly Value			Anomaly Value	
Year	Sahel	G. Coast	Year	Sahel	G. Coast
1970	1.98	1.05	1982	-0.77	-0.95
1971	1.31	1.05	1983	-1.25	-1.16
1974	2.47	1.36	1986	-0.50	-1.00
1979	2.51	0.90	1993	-1.00	-0.96
1999	0.75	1.90	1994	-0.94	-1.05
2006	0.64	0.81			
2007	1.91	1.28			

The global scale patterns in the +/+ and -/- composite anomalies were very similar to those associated with LN and EN, respectively. To investigate this further, we constructed composite anomalies for the years in which a strong LN or EN event (see Chapter IV, Section B.1) occurred during April-December (i.e., during April-Jun (AMJ), one season prior to JAS, during JAS, or during October-December (OND), one season after JAS). The resulting sets of years are shown in Table 5.

Table 5.   Years in which a strong LN or EN event occurred during AMJ, JAS or OND.

Strong LN	Strong EN
1970	1972
1971	1982
1973	1983
1974	1986
1975	1987
1988	1991
1999	1992
2007	1993
	1994
	1997
	1998
	2006

A comparison of Tables 4 and 5 showed that there was not a strict one-to-one relationship between strong ENLN events and strong non-dipole rainfall anomalies in TWA. However, there is a clear association of +/+ events and LN events, and -/- events and EN events. This led us to focus our composite anomaly analyses on a periods in which both: (1) a strong LN event and a +/+ event occurred; or (2) a strong EN event and a -/- event occurred. These periods are shown in Table 6. We used the composite anomalies for these years to explore: (1) the relationships between ENLN and TWA rainfall; and (2) the potential value of ENLN indices and long range ENLN predictions as predictors of TWA rainfall. Note that the years composited for the -/- composites (Table 4) and for the -/- *and* strong EN composites (Table 6) are the same, indicating that -/- events are strongly associated with EN events.

Table 6.   Years during 1970-2007 in which both a strong LN event and a TWA +/+ event occurred (left column) and years in which both a strong EN event and a TWA -/- event occurred (right column).

Strong LN & +/+ Anomaly Value	Strong EN & -/- Anomaly Value
1970	1982
1971	1983
1974	1986
1999	1993
2007	1994

3.   Correlation Analyses

This study made extensive use of correlation analyses to identify teleconnections and other climate relationships. Correlations were done using routines provided by the ESRL correlations website (Note: Insert website info) and Microsoft Excel.   The correl function in Excel returns the correlation coefficient of two equal-sized arrays (Microsoft Excel 2003) using:

$$Correl(X,Y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$

Here, X and Y are the arrays to be correlated, x (y) is the actual value for each i matrix node, and x-bar (y-bar) is the mean for the whole array. The significance level of the correlations was determined using the two-tailed Student's t-test method.

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V.   RESULTS

A.   TIME SERIES OF PRECIPITATION VARIABILITY

1.   Tropical West African Precipitation Time Series

Figure 14 shows the total JAS PRATE time series for the Sahel and Guinea coast regions for all of the years available in the NCEP/NCAR reanalysis. Both time series show large decadal variability prior to 1968 and considerable interannual variability, especially prior to 1968. The reduction in variability after 1968 is indicated by the reduction in the standard deviation for the pre-1968 and post-1968 periods. For the Sahel region, that standard deviation changed from 77.77 kg m^{-2} s^{-1} during 1948-68 to 28.75 kg m^{-2} s^{-1} during 1970-2007. For the Guinea coast region, the standard deviation changed from 47.29 kg m^{-2} s^{-1} during 1948-68 to 29.38 kg m^{-2} s^{-1} during 1970-2007.

Figure 14 also shows that, prior to (after) 1968, the interannual variations in the two regions tended to be opposite (similar) to each other. The correlation between total JAS precipitation rate for the Sahel and Guinea coast regions for the 1948-68 period was -0.54 (significant at the 99% level). Conversely, the correlation coefficient between the two regions for the 1970-2007 period was +0.48 (significant at the 99% level). The long-term mean JAS precipitation rates for the two regions were roughly similar during 1948-68, with the Sahel somewhat wetter than the Guinea coast (about 240 kg m^{-2} s^{-1} and 175 kg m^{-2} s^{-1}, respectively). But during 1970-2007, the Sahel was considerably drier than during 1948-1968, with a long term mean JAS PRATE of about 100 kg m^{-2} s^{-1}, while the Guinea coast was considerably wetter, with a long term mean JAS PRATE of about 245 kg m^{-2} s^{-1}.
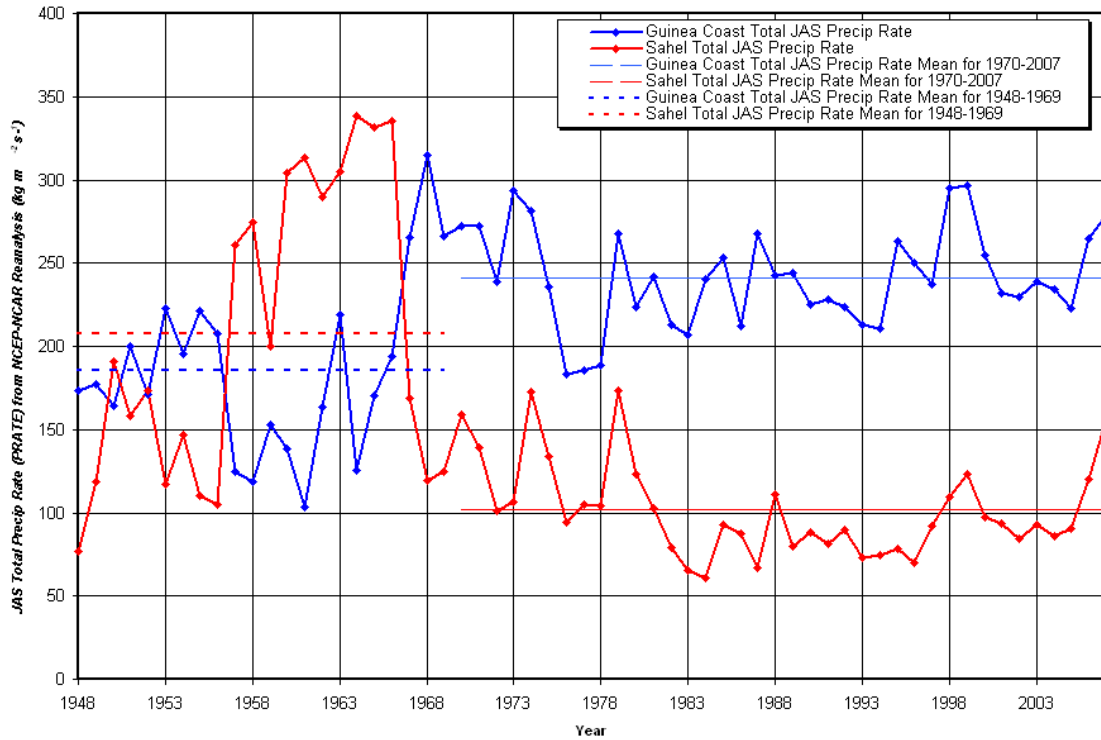
Figure 14.   Time series of monthly July-August-September (JAS) PRATE during 1948-2007 for the Sahel region (red) and Guinea coast region (blue). These regions are defined in Chapter I, Section B. The long-term mean JAS precipitation rate for 1948-1967 (1970-2007) for the Sahel is shown by the dashed blue (solid blue) horizontal line and for the Guinea coast by the dashed red (solid red) horizontal line.

2.   Normalized TWA PRATE Anomaly Time Series

Figure 15 shows the normalized JAS PRATE anomaly time series for the Sahel and Guinea coast regions.   This anomaly time series highlights the interannual variability seen in Figure 14. The non-dipole +/+ (wet) and -/- (dry) years in both TWA regions are indicated by the red and blue circles. The red and blue ovals indicate groupings of relatively these wet and dry years, respectively. Note the decadal-scale pattern indicated by these non-dipole +/+ and -/- groupings. The 1970s had four +/+ years and zero -/- years. The 1980s and early 1990s had zero +/+ years and five -/- years. The last decade had three +/+ years and zero -/- years. Note also that there were only three years during 1970-

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2007 in which clear dipoles occurred — that is, years in which the Sahel and Guinea coast regions had strong (normalized anomaly magnitude greater than 0.5). This indicates that in the last four decades, non-dipole variations have been the dominant variation pattern, and dipole variations identified in prior studies (e.g., Ward 1998; Nicholson 2008a) have been relatively uncommon. This also indicates the importance of the non-dipole variations that are the focus of our study.
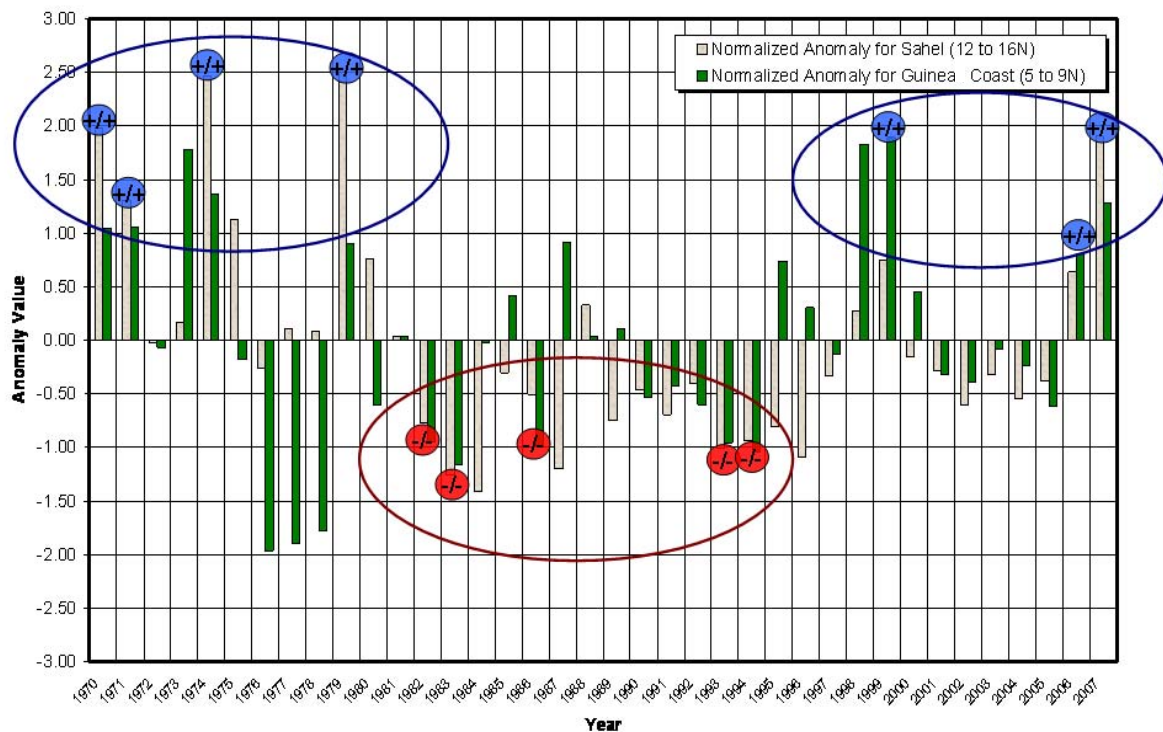
Figure 15.   Normalized JAS PRATE anomaly for 1970-2007. Khaki – Sahel region. Green – Guinea coast region. A larger anomaly value indicates a greater departure from the 1970-2007 JAS PRATE mean (Figure 11). Blue +/+ circles above anomaly bars indicate both regions had a normalized anomaly value greater than 0.5 for the year. Red -/- circles below anomaly bars indicate both regions had a normalized anomaly value less than -0.5 for the year. Blue and red ovals indicate temporal groupings of non-dipole wet and dry years.

B.   CORRELATIONS BETWEEN TWA PRECIPITATION AND ENLN

The correlation between the normalized JAS PRATE anomaly for the two TWA regions and the MEI for 1970-2007 are shown in Table 7 and Figure 16. The MEI values are bimonthly values for Sep/Oct through Aug/Sep. Thus, Table 8 represents: (1) correlations in which the JAS PRATE anomaly lags the MEI (for Sep/Oct through Jun/Jul); and (2) simultaneous correlations (for Jul/Aug through Aug/Sep).   All the correlations significant at the 95% level or greater are negative, indicating that high (low) rainfall periods are associated with LN (EN) events.   The correlations also indicate that ENLN events may be useful as predictors of JAS rainfall variations in Sahel region at leads of up to seven months, and in the Guinea coast region at leads of up to three months.

Table 7.   Correlation between normalized JAS PRATE anomaly values and bimonthly MEI values for 1970-2007. Yellow highlights the correlation coefficients that are significant at the 95% or greater level.

Normalized JAS PRATE Anomaly Correlation with MEI for 1970-2007		
MEI Month	Sahel	Guinea Coast
SEPT/OCT	-0.20	0.01
OCT/NOV	-0.16	0.02
NOV/DEC	-0.19	-0.01
DEC/JAN	-0.18	-0.06
JAN/FEB	-0.23	-0.06
FEB/MAR	-0.36	-0.14
MAR/APR	-0.40	-0.15
APR/MAY	-0.45	-0.21
MAY/JUN	-0.49	-0.32
JUN/JUL	-0.49	-0.41
JUL/AUG	-0.45	-0.42
AUG/SEPT	-0.44	-0.47
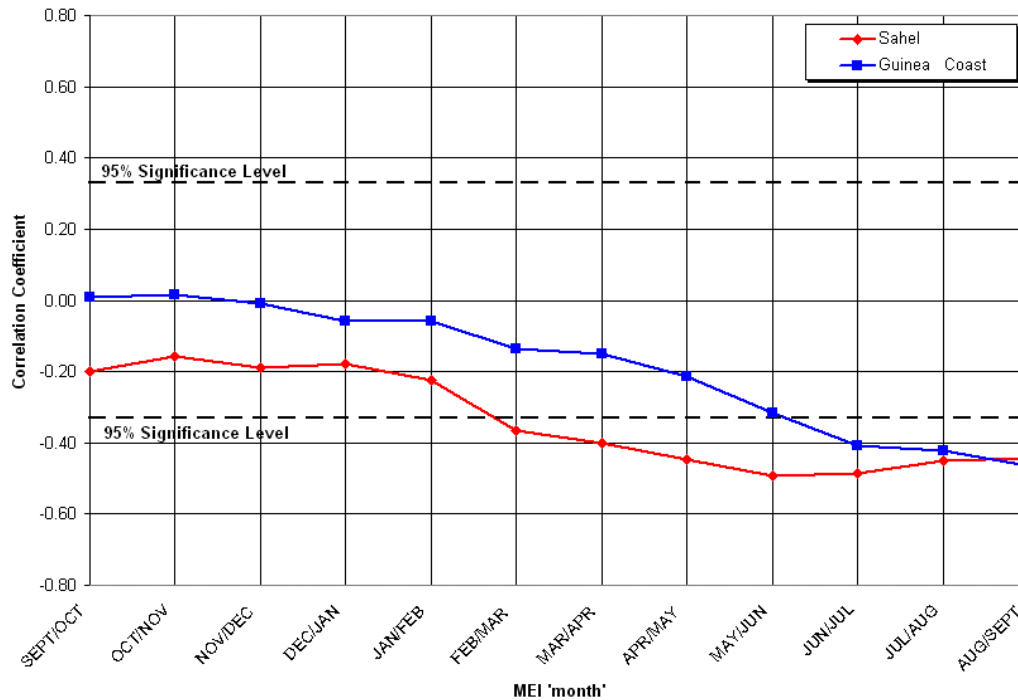
Figure 16.   Correlations between normalized JAS PRATE anomaly and the bimonthly MEI for 1970-2007 for Sahel region (red) and Guinea coast region (blue). Dashed lines indicate correlations significant at the 95% level.

C.   COMPOSITE ANALYSES

Our composite analyses examined three general cases: (1) composites of +/+ (or -/-) periods; (2) composites of strong LN (or EN) periods; and (3) composites of +/+ and strong LN (or -/- and strong EN) periods. From here forward, the type 3 composites will be referred to as "+/+ | LN" or "-/- | EN" composites. The OLR composite anomaly plots in Figure 17 are examples of the three composite anomalies types.
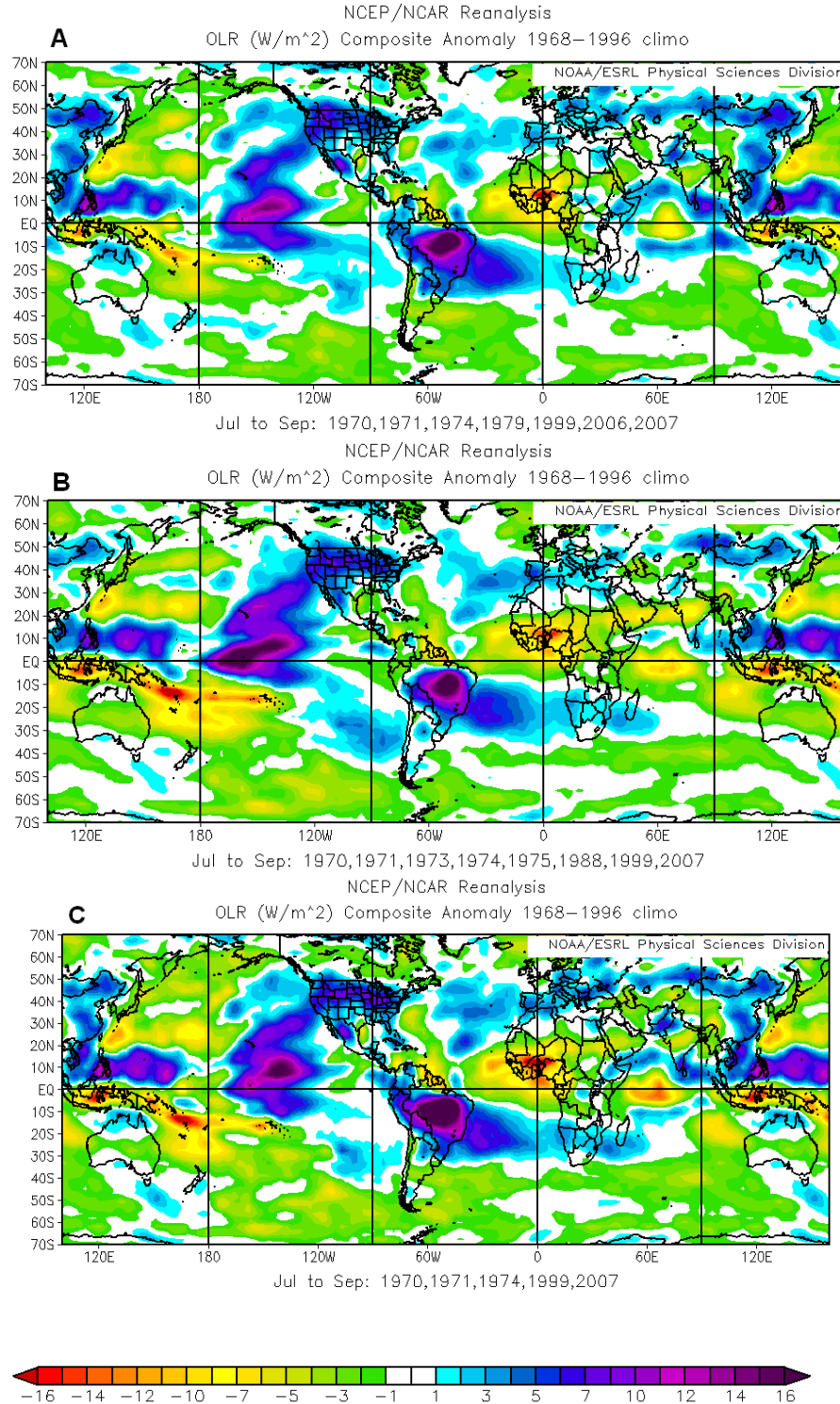
Figure 17.   JAS OLR composite anomaly plots for 1970-2007 study period in W m^{-2}. (A) JAS OLR anomaly for all +/+ years. (B) JAS OLR anomaly for all strong LN years. (C) JAS OLR anomaly for all +/+ *and* strong LN years.

Figure 17 shows strong similarities between the composite anomalies for all +/+ years and for all strong LN years, particularly over the tropical Pacific and Atlantic basins. Comparisons of the three types of composite anomalies were used to aid in the identification of climate patterns and processes (e.g., those associated with tropical Rossby-Kelvin waves).

1. Composite PRATE Anomalies

The African region LTM JAS PRATE for the base period 1968-1996 is shown in Figure 18. Note that the TWA rainfall occurs is concentrated in a zonal band between approximately 4°N and 16°N. The Sahel and Guinea coast regions (see Chapter I, Section B) lie within this band. LTM PRATE maps are important in interpreting PRATE anomalies. For example, LTM PRATE maps aid in distinguishing anomalies that are due to: (1) changes in PRATE amounts; (2) spatial shifts in PRATE; and (3) temporal shifts in PRATE.
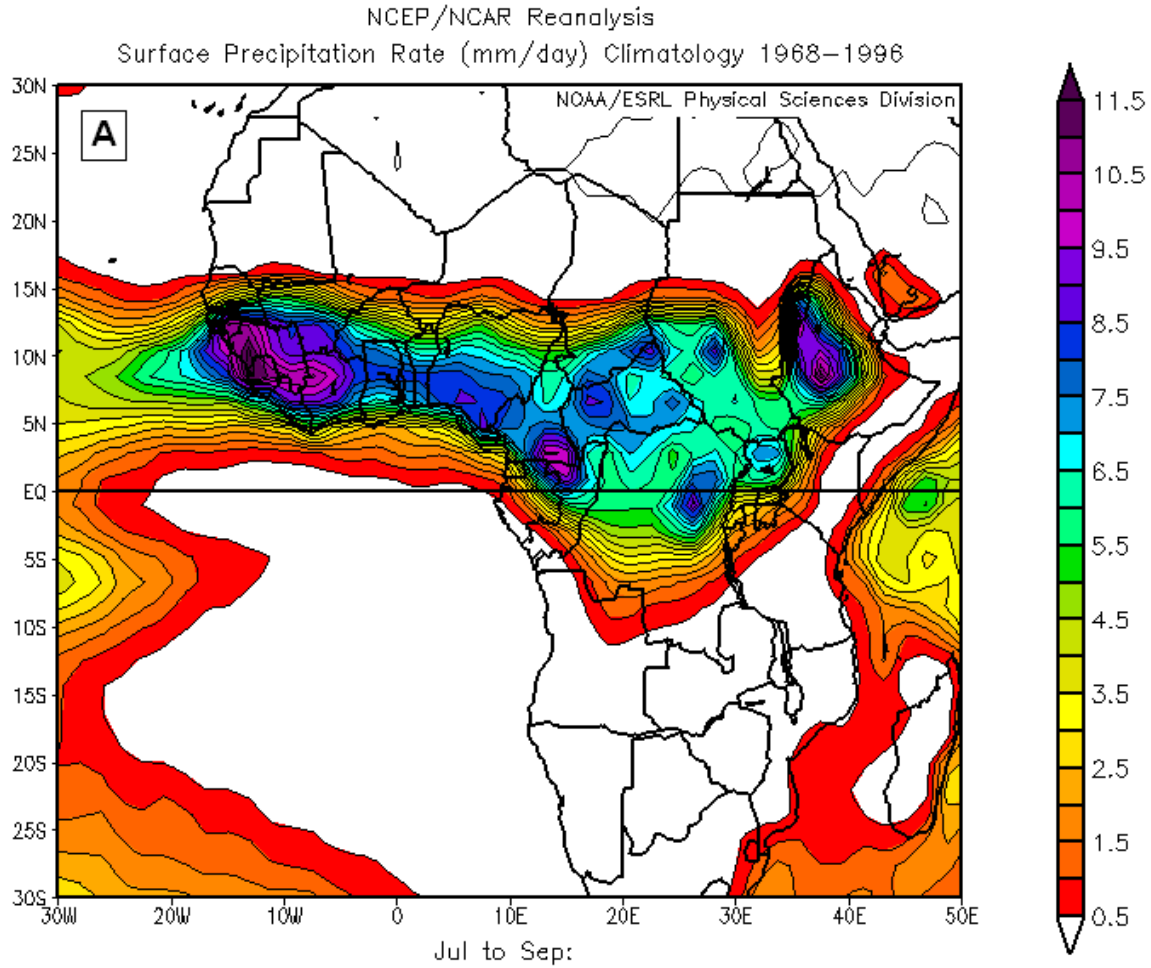
Figure 18.   LTM JAS PRATE for the African region in mm day^{-1}.

Figures 19 and 20 show the composite mean (A) and composite anomaly (B) for JAS PRATE for the +/+ and -/- years, respectively. Notice that the JAS PRATE anomaly for the +/+ (-/-) years is almost entirely positive (negative) throughout TWA, as expected for these non-dipole composites (see Chapter I, Section C.3; and Chapter IV, Section C.3). Comparisons of Figures 18-20 indicate that the PRATE anomalies are largely the result of changes in rainfall amounts, rather than spatial shifts in rainfall. Figures 19-20 suggest that the TWA rainfall anomalies may have some relationship to rainfall anomalies extending westward from TWA over the North Atlantic and eastward and southeastward from TWA into the eastern Sahel and central equatorial Africa.
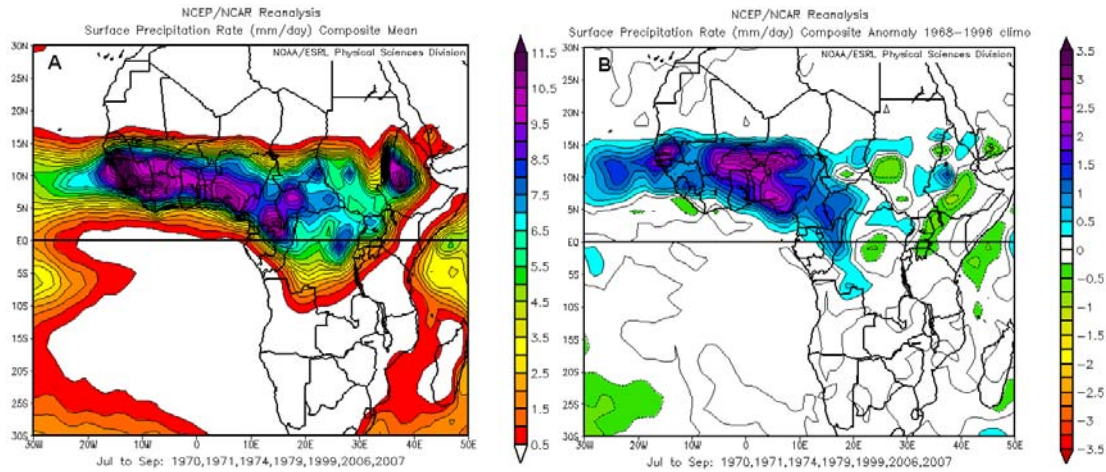
Figure 19.   (A) JAS PRATE composite mean for +/+ years. (B) JAS PRATE composite anomaly for +/+ years. Units: mm day^{-1}.
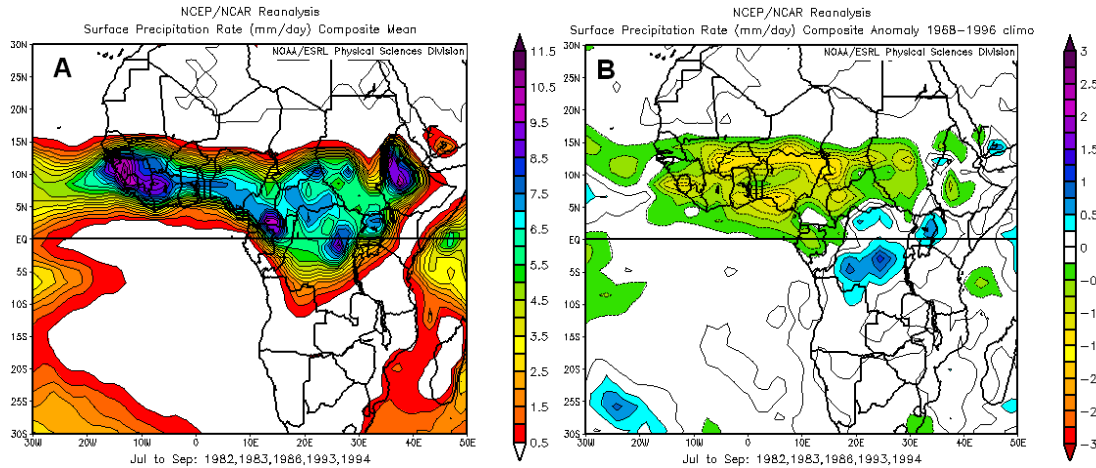
Figure 20.   (A) JAS PRATE composite mean for -/- years. (B) JAS PRATE composite anomaly for -/- years. Units: mm day^{-1}.

2.   Equatorial Rossby – Kelvin Waves

In an effort to understand the global scale atmospheric dynamics that contribute to anomalously high (low) JAS PRATE across TWA, the +/+ (-/-) composite anomalies for geopotential height (GPH) were developed for 200, 600, 850, and 925 hPa.

Figure 21 shows the JAS 200 hPa GPH composite anomalies for the +/+ years (panel A) and the strong LN years (panel B). The anomalous equatorial Rossby-Kelvin (R-K) wave pattern (see Chapter I, Section C.4.d) is evident in both panels and highlighted in panel A. This pattern is consistent with anomalous tropospheric cooling over the central tropical Pacific induced by anomalously cool SSTs at the equator associated with LN. The corresponding pattern for the strong LN composite (Figure 22) is similar but with a more continuous zonal band of negative anomalies in the tropics. For both composites, the GPH anomalies over TWA indicate anomalously westward winds at 200 hPa and a stronger than average Tropical Easterly Jet (TEJ).
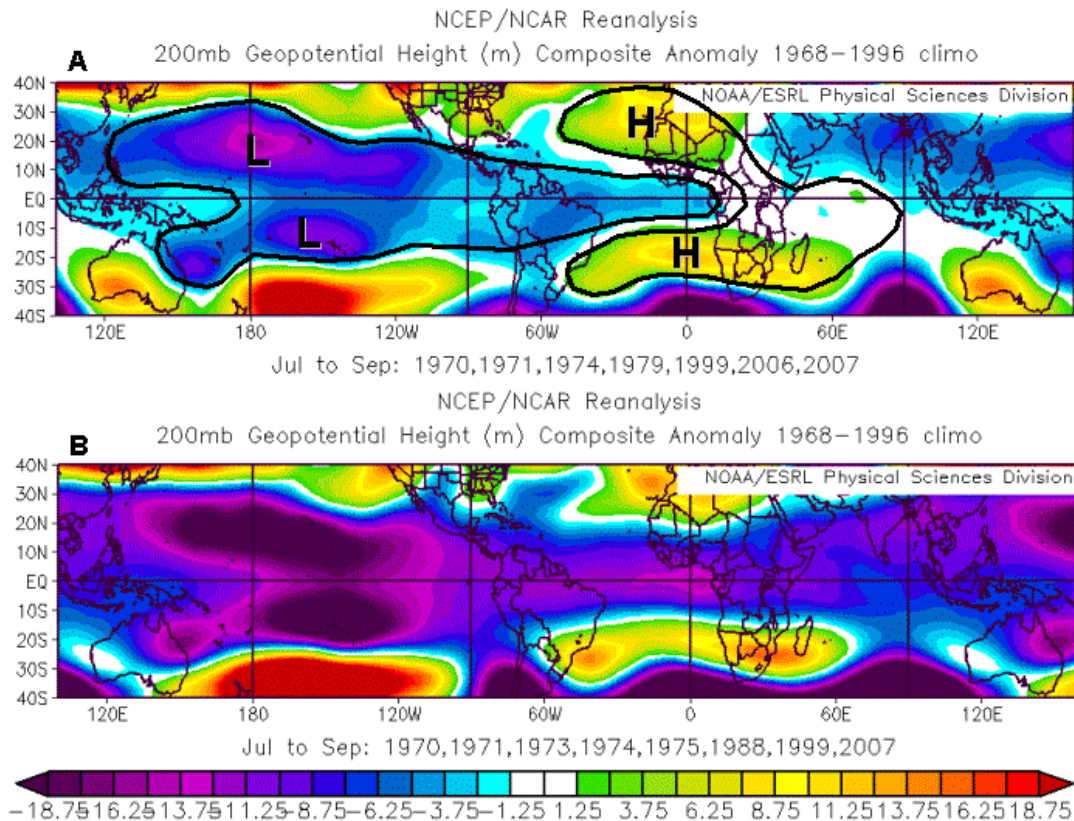
Figure 21.   JAS 200 hPa GPH composite anomalies for (A) +/+ years, and (B) strong LN years. The anomalous equatorial Rossby-Kelvin wave pattern is outlined by a solid black line in panel (A), with the main positive and negative anomalies marked with H and L, respectively. Units: m.

Figure 22 shows the JAS 200 hPa GPH composite anomalies for the -/- years (panel A) and the strong EN years (panel B). The height anomalies for the -/- years reveal an anomalous equatorial R-K wave pattern that is opposite in sign to the +/+ years' signature in the central and western Pacific, as well as across the tropical Atlantic and into TWA. The EN composite anomalies in panel B are similar to but stronger than those for the -/- composite in panel A. The R-K wave patterns in both panels of Figure 22 are consistent with anomalous tropospheric warming in the central tropical Pacific associated with anomalously warm SSTs in that region during strong EN years. For both composites, the GPH anomalies over TWA indicate anomalously eastward winds at 200 hPa and a weaker than average Tropical Easterly Jet (TEJ).

The results shown in Figures 21-22 indicate that equatorial R-K wave dynamics are part of the mechanism by which EN and LN events alter TWA precipitation. The low frequency nature of equatorial R-K waves provides dynamical support to the hypothesis that EN and LN events may be useful long lead predictors of TWA rainfall (see Chapter V, Section B).
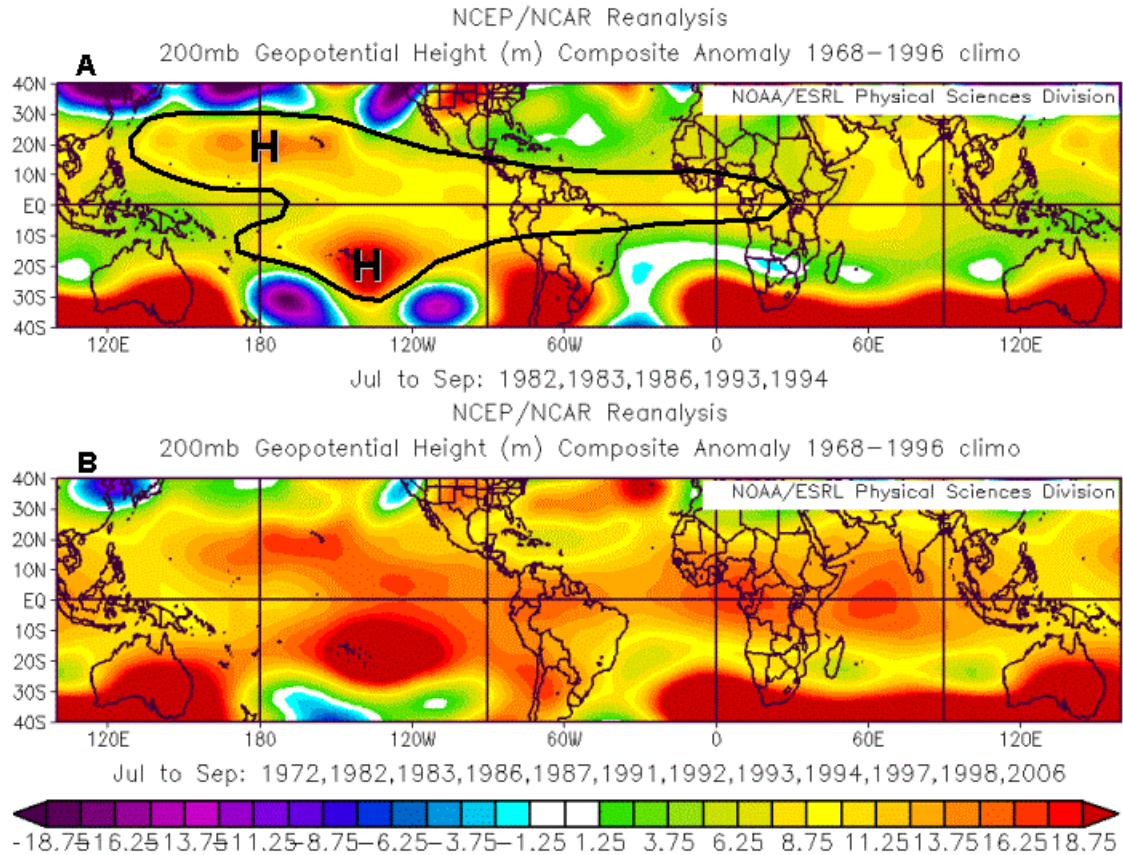
Figure 22.   JAS 200 hPa GPH composite anomalies for (A) -/- years, and (B) strong EN years. The anomalous equatorial Rossby-Kelvin wave pattern is outlined by a solid black line in panel (A), with the main positive and negative anomalies marked with H. Units: m.

3.   Southern Hemisphere Rossby Wave Trains

Figures 23 and 24 show the JAS +/+ | LN and -/- | EN composite anomalies for GPH at 200, 600, and 850 hPa. In these near-global views, an anomalous SH Rossby wave train is apparent, arching from the tropical Pacific into the TWA region. The wave trains are opposite for the +/+ | LN and -/- | EN cases. However, in both cases, the wave trains originate near the SH Rossby lobe of the anomalous equatorial Rossby-Kelvin waves shown in Figures 21-22. The Rossby wave trains also have an equivalent barotropic structure in the extratropics, as indicated by the similar extratropical anomaly patterns at all three

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levels. These wave trains are consistent with the results of Karoly (1989), Ford (2000), and others who have associated EN and LN events with anomalous Rossby wave trains arching through the fall-winter hemisphere (the SH for JAS).

These results suggest that extratropical Rossby wave dynamics are part of the mechanism by which EN and LN events alter TWA precipitation. The low frequency nature of extratropical Rossby waves provides dynamical support to the hypothesis that EN and LN events may be useful long lead predictors of TWA rainfall (see Chapter V, Section B).

The corresponding anomalous equatorial R-K waves (Figures 21-22) and anomalous extratropical Rossby wave trains (Figures 23-24) lead to anomalies of the same sign over tropical Africa (e.g., negative 200 hPa anomalies in the +/+ | LN case). This indicates that the two wave responses to ENLN conditions in the tropical Pacific constructively interfere with each other over tropical Africa. It also indicates that the TWA rainfall response to ENLN may be sensitive to the nature of the ambient extratropical circulation that influences the extratropical wave train position, orientation, and amplitude (e.g., Karoly 1989). If so, this may help explain why strong LN (EN) events have not always produced +/+ (-/-) rainfall events in TWA.
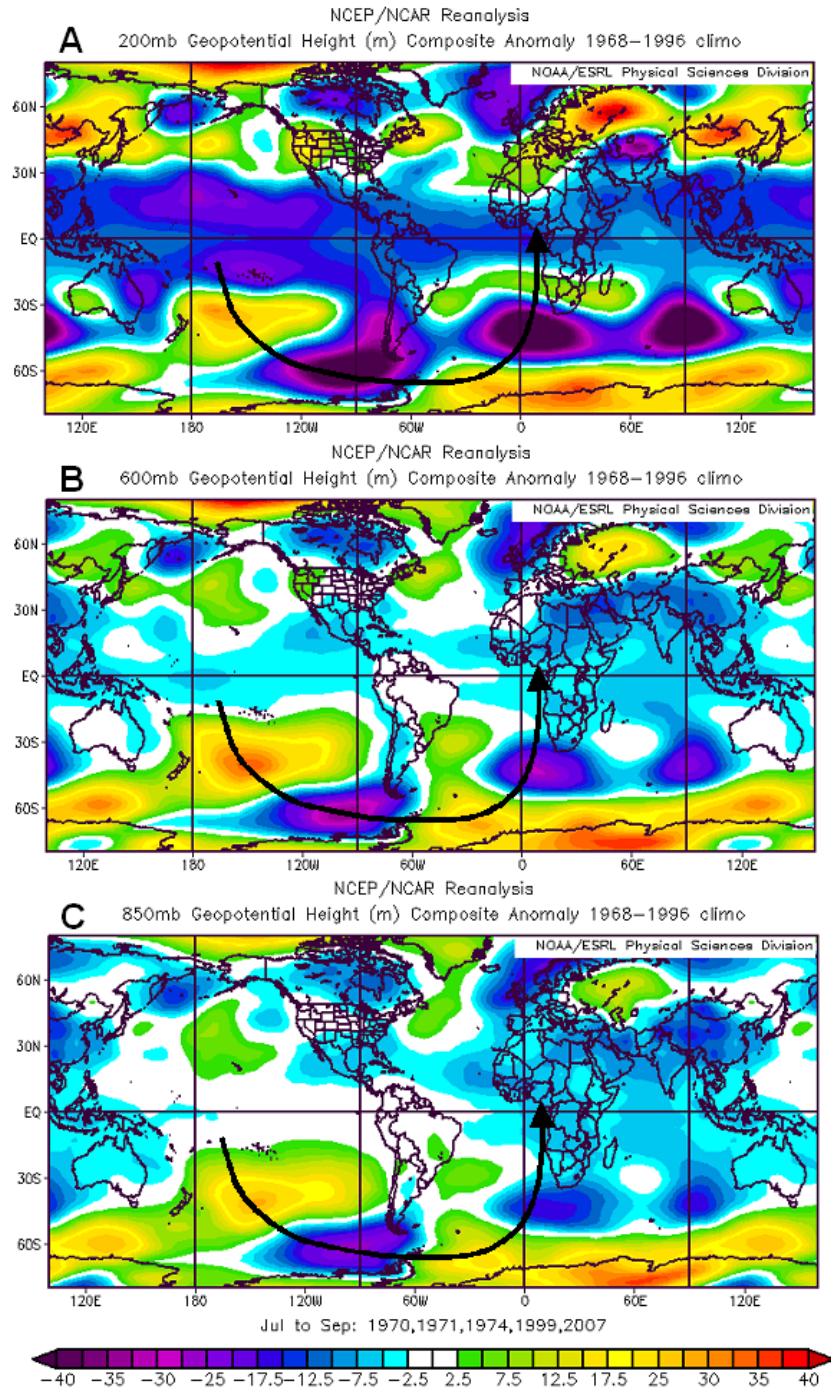
Figure 23.   JAS GPH composite anomalies for +/+ | LN years at (A) 200 hPa, (B) 600 hPa, and (C) 850 hPa. The solid black arrows indicates the propagation of anomalous wave energy in the anomalous SH Rossby wave train into TWA. Units: m.
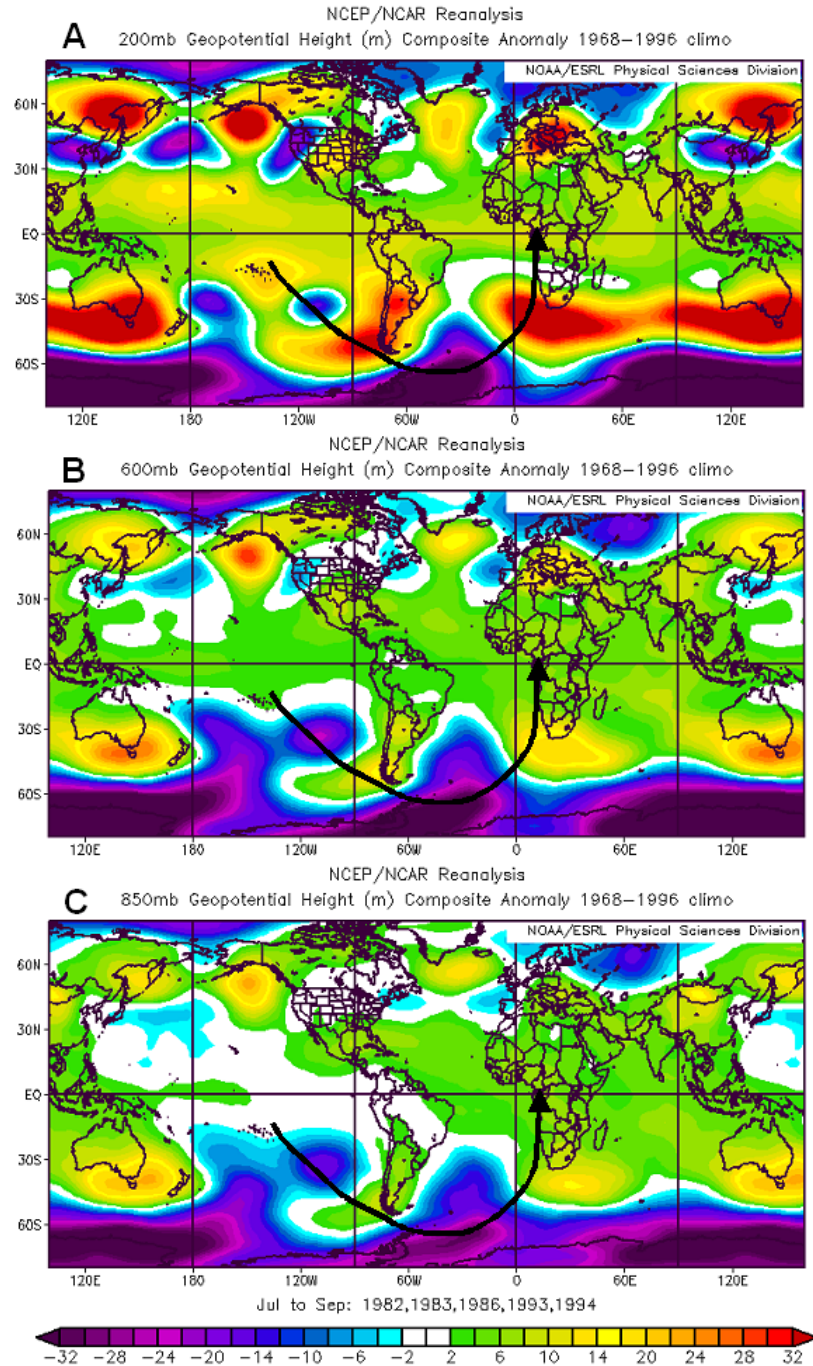
Figure 24.   JAS GPH composite anomalies for -/- | EN years at (A) 200 hPa, (B) 600 hPa, and (C) 850 hPa. The solid black arrows indicates the propagation of anomalous wave energy in the anomalous SH Rossby wave train into TWA. Units: m.

4. Teleconnections to TWA Precipitation

Figure 25.   Long-term mean speeds and location of the Tropical Easterly Jet (TEJ) at 200 hPa over Africa in July-August-September (JAS). Arrow highlights location and direction of TEJ. Based on NCEP/NCAR Reanalysis data for the long-term mean base period of 1968-1996.

Figure 25 shows the long-term mean speed and location of the TEJ over Africa in JAS. As previously mentioned in Chapter 1, Section C, subsection 4a, the TEJ is an important factor in the variability associated with TWA rainfall.

Figure 26 compares the JAS 200 hPa zonal wind composite anomalies for the +/+ | LN years and the -/- | EN years. The differences are striking. The +/+ | LN anomalies are easterly across all of TWA, with a strongly concentrated easterly anomaly between the equator and 10°S (Figure 26A). This pattern indicates an anomalous strengthening of the TEJ and a southward displacement from its LTM position near 5°N. Such strengthening and displacement would tend to enhance and widen the area of vertical ascent and precipitation over TWA (cf. Nicholson and Webster (2007); Nicholson (2008a)).

The -/- | EN anomalies include a strongly concentrated westerly anomaly between the equator and 10°S (Figure 26B). This indicates an anomalously weak TEJ and a strengthening and equatorward displacement of the SH

subtropical westerlies. These anomalies are consistent with anomalously weak vertical ascent and low rainfall over TWA (cf. Nicholson and Webster 2007; Nicholson 2008a).

Figure 26.   JAS 200 hPa zonal wind composite anomalies for: (A) +/+ | LN years; and (B) -/- | EN years. Negative (positive) anomalies indicate easterly (westerly) anomalies. Black arrows show anomalous wind directions. Units: m s^{-1}.

Figure 27 shows the long-term mean speed and location of the AEJ over Africa in JAS. As previously mentioned, the AEJ is an important factor in the variability associated with TWA rainfall (see Chapter 1, Section C, subsection 4a).
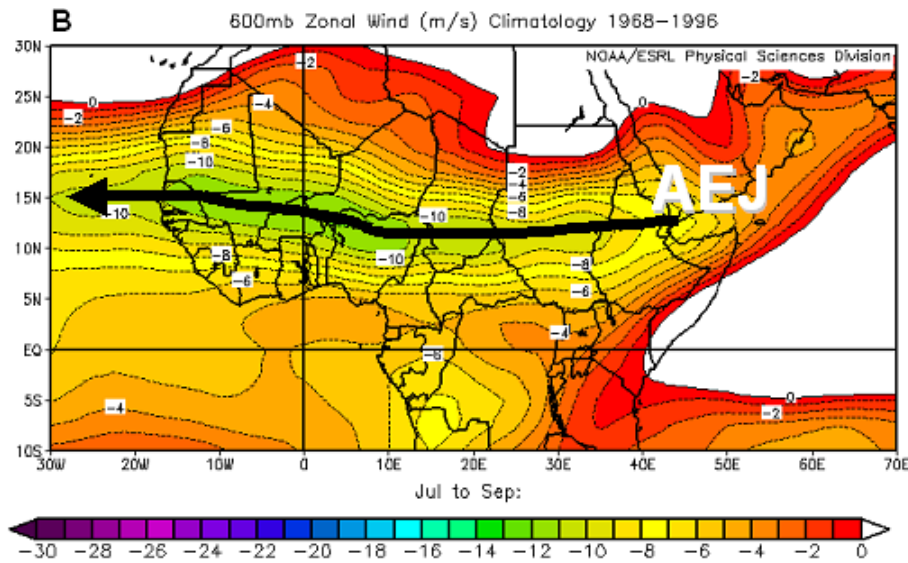
Figure 27.   Long-term mean speeds and location of the African Easterly Jet (AEJ) at 600 hPa over Africa in July-August-September (JAS). Arrow highlights location and direction of AEJ. Based on NCEP/NCAR reanalysis data for the long-term mean base period of 1968-1996

Figure 28 is the same as Figure 26 but for 600 hPa.   At this level, circulation anomalies associated with the AEJ are revealed.   The +/+ | LN composite shows a strong westerly anomaly between 5° and 10°N over TWA, and a strong easterly anomaly between 15° and 20°N. This pattern indicates a northward displacement of the AEJ over TWA. A northward displacement of the AEJ has been proposed as one of the criteria necessary for the development of a +/+ mode in TWA rainfall (Nicholson 2008a).

The -/- | EN composite shows an easterly anomaly between 4° and 10°N and a slight westerly anomaly between 12° and 20°N. This pattern indicates a slight southward displacement of the AEJ from its mean position at approximately 14°N, and a slight contraction of the region for vertical ascent between the AEJ and the TEJ. This is consistent with anomalously low rainfall over TWA.

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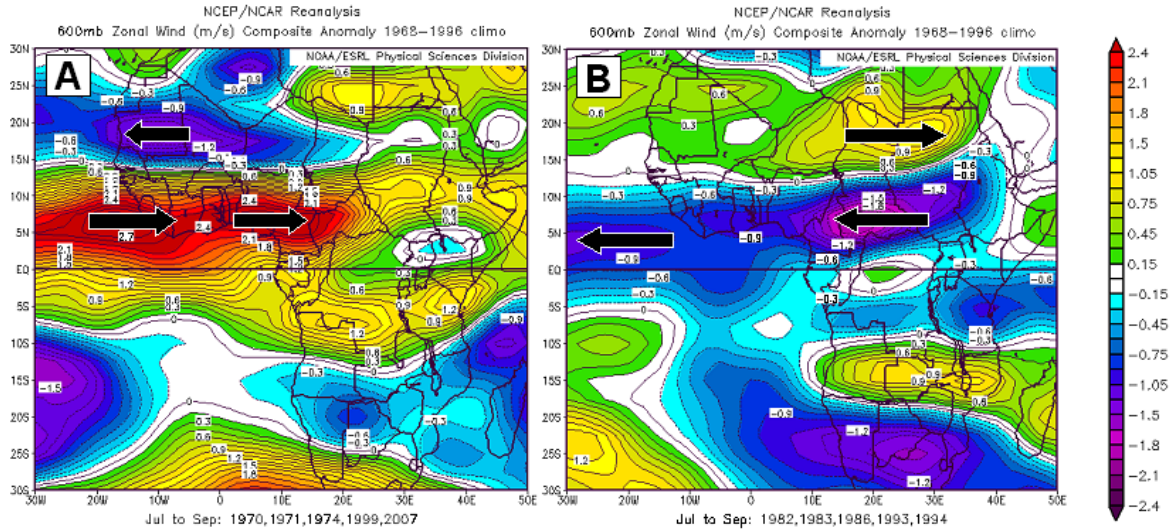
Figure 28.   JAS 600 hPa zonal wind composite anomalies for: (A) +/+ | LN years; and (B) -/- | EN years. Negative (positive) anomalies indicate easterly (westerly) anomalies. Black arrows show anomalous wind directions. Units: m s^{-1}.

Figure 29 shows the long-term mean speed and location of the SWMJ over Africa in JAS. The SWMJ contributes to the moisture distribution in TWA (cf. Nicholson and Webster 2007).
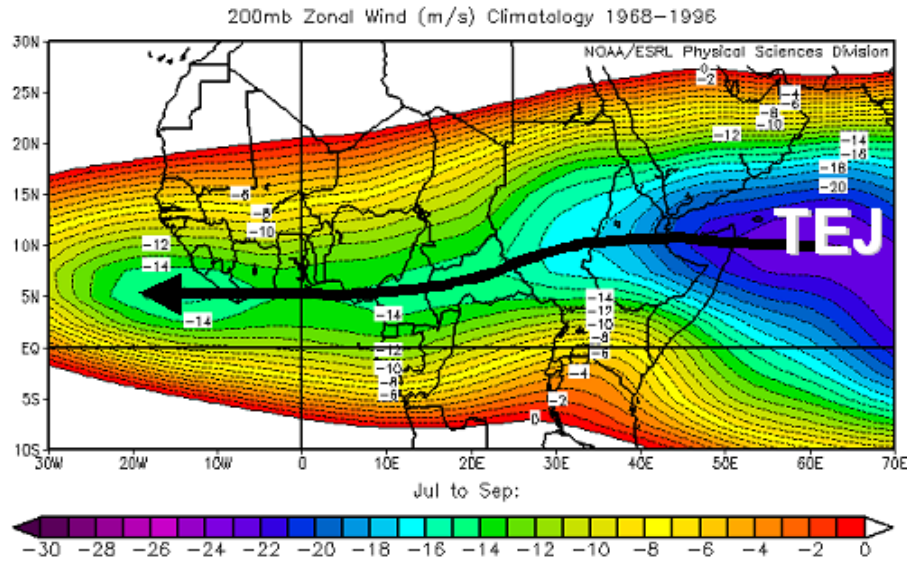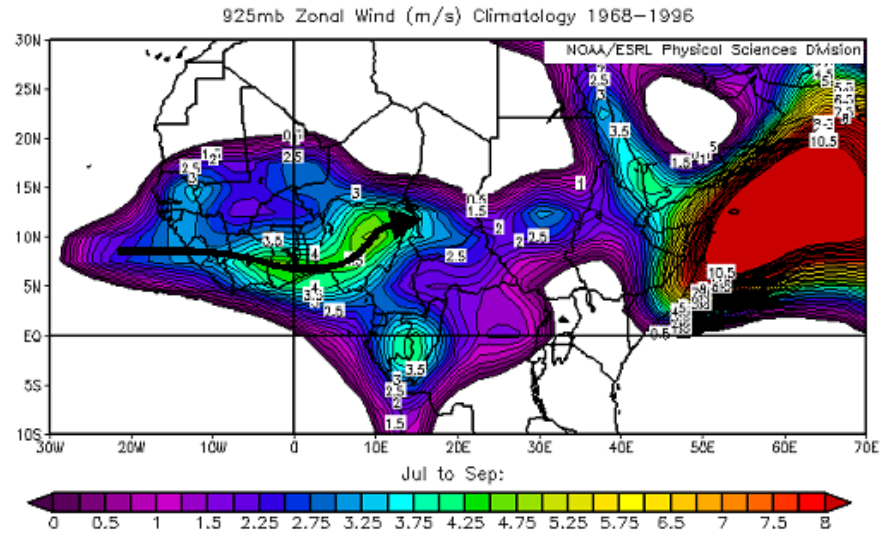

Figure 29.   Long-term mean speeds and location of the Southwesterly Monsoon Jet (SWMJ) at 925 hPa over Africa in July-August-September (JAS). Arrow highlights location and direction of SWMJ. Based on NCEP/NCAR reanalysis data for the long-term mean base period of 1968-1996.

Zonal wind anomalies at 925 hPa were investigated for insight into the behavior of the low level Southwesterly Monsoon Jet (SWMJ) during +/+ | LN years and -/- | EN years (Figure 30). The +/+ | LN anomaly patterns (Figure 30A) indicate a strong intensification of the SWMJ into the western and southern parts of TWA. This pattern would tend to result in increased low-level moisture advection into the region of vertical ascent between the TEJ and the AEJ. This would likely contribute additional moisture for convective activity, consistent with anomalously high rainfall in TWA. The -/- | EN anomaly patterns (Figure 30B), show an anomalously weak SWMJ, corresponding to reduced moisture advection into TWA, and reduced convection and rainfall over TWA.
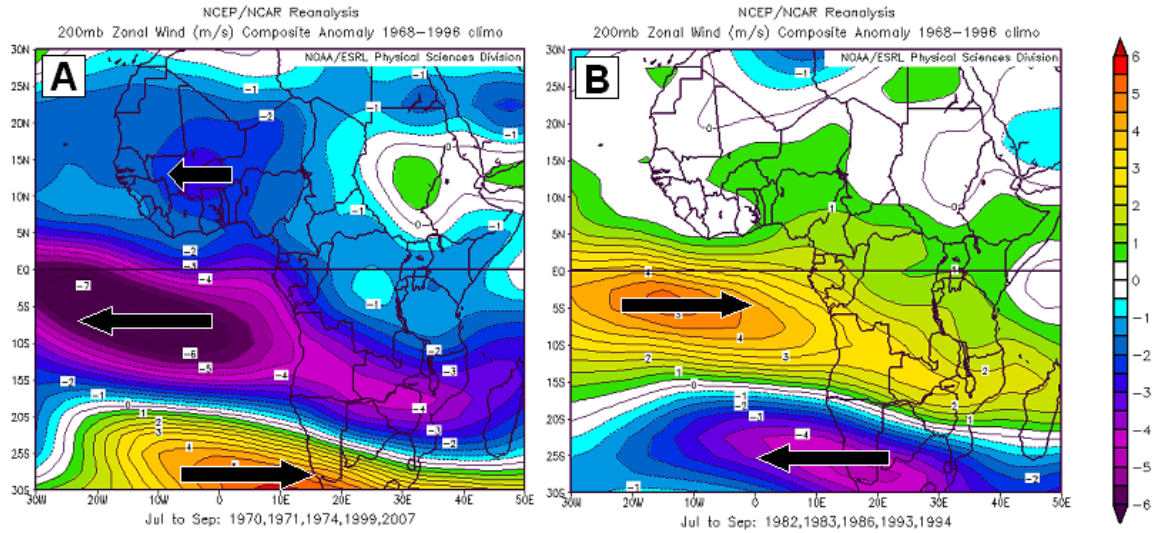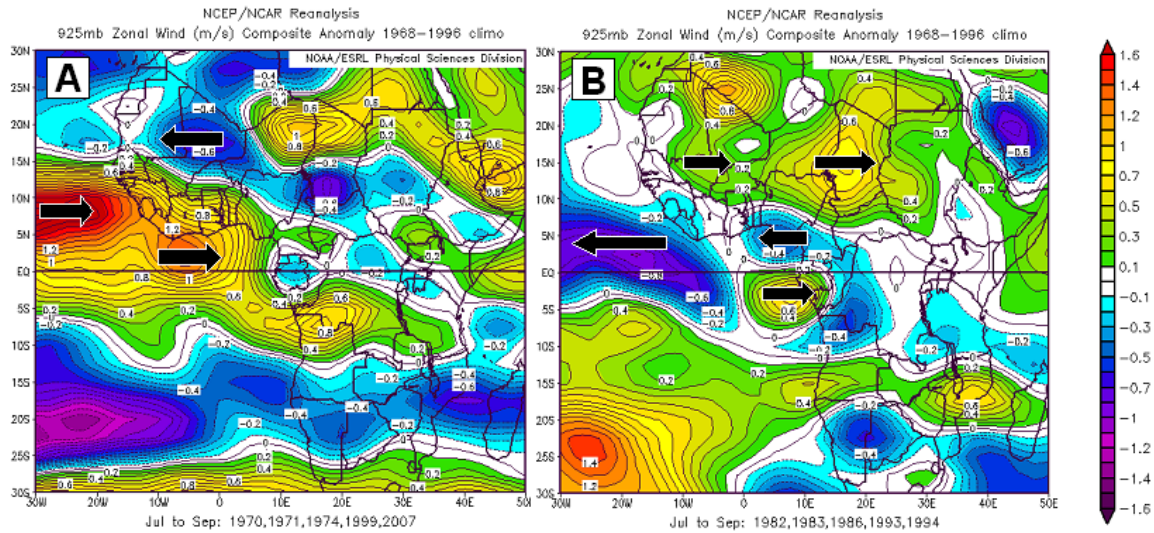

Figure 30.   JAS 925 hPa zonal wind composite anomalies for: (A) +/+ | LN years; and (B) -/- | EN years. Negative (positive) anomalies indicate easterly (westerly) anomalies. Black arrows show anomalous wind directions. Units: m s^{-1}.

A comparison of Figures 21-22 with Figures 23-24 indicates that the major upper tropospheric wind anomalies in the tropical African region are strongly related to anomalous equatorial R-K waves and extratropical Rossby wave trains generated by EN and LN events. In addition, the vertical structure of the 200 and 925 hPa zonal wind anomalies shown in Figures 26 and 30 are consistent with the expected vertical structure for equatorial R-K waves, with a reversal of the

equatorial circulation anomalies from the upper troposphere to the lower troposphere. Thus, the impacts of EN and LN events on TWA rainfall seem to occur through global scale low frequency wave processes that alter winds throughout the troposphere in the tropical African region. These wind changes then lead to alterations in moisture advection, deep convection, and rainfall.

To further investigate this hypothesis, we constructed meridional cross sections of the zonal wind and omega to further examine how changes in global scale, low frequency wave activity and horizontal winds lead to changes in TWA rainfall. Figure 31 shows a meridional cross section of LTM JAS zonal wind and the locations of the TEJ, AEJ, and SWMJ over TWA: TEJ - 150-200 hPa and 5°N; AEJ - 600 hPa and 14°N; and SWMJ - 925 hPa and 7°N.

Figure 31.   Meridional cross section of LTM JAS zonal wind from 30°S to 30°N, and averaged over 10°E to 5°W. TWA occurs between approximately 5°N and 15°N. Bold letters mark the three major zonal winds important to JAS rainfall over TWA. Units: m s^{-1}.

Figure 32A shows in meridional cross section the JAS zonal wind anomalies over TWA for the +/+ | LN years. Note the strong easterly anomaly centered at 200 hPa and 8°S, the westerly anomaly centered at 700 hPa and 5°N, and the easterly anomaly centered at 650 hPa and 17°N. These anomalies support the indications of Figure 26A and 28A that during +/+ | LN years: (1) the TEJ is anomalously strong and displaced equatorward from its LTM position; and (2) the AEJ is displaced poleward from its LTM position.
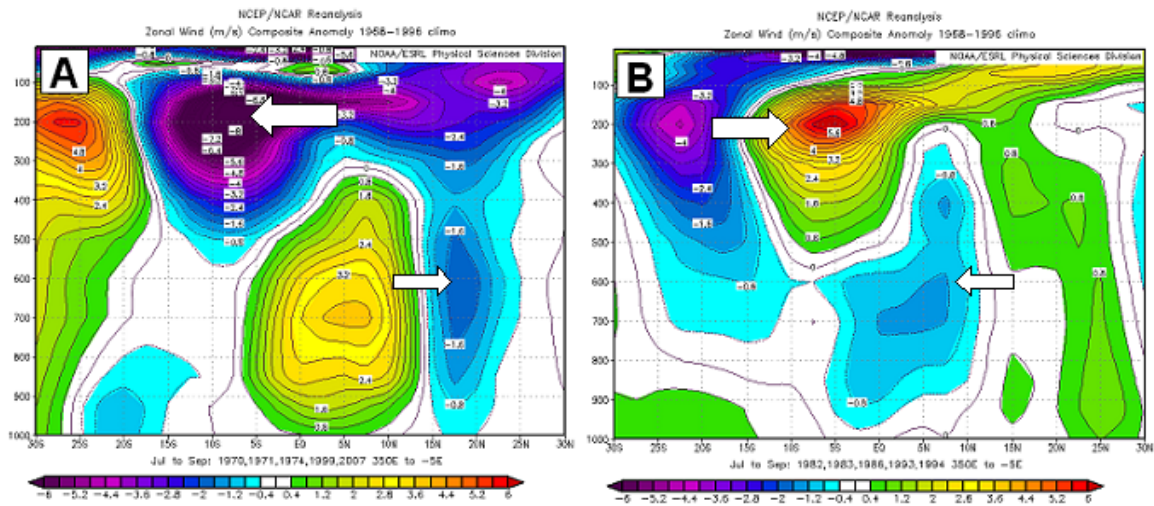
Figure 32.   Meridional cross sections of JAS zonal wind composite anomalies for (A) +/+ | LN, and (B) -/- | EN cases. Negative (positive) values indicate easterly (westerly) anomalies. Cross sections extend from 30°S to 30°N, and are averaged over 10°E to 5°W. TWA occurs between approximately 5°N and 15°N. Arrows highlight shifts in positions of TEJ and AEJ. Units: m s^{-1}.

Figure 32B shows in meridional cross section the JAS zonal wind anomalies over TWA for the -/- | EN years. Note the strong westerly anomaly centered at 200 hPa and 5°S, and the easterly anomaly centered at 650 hPa and 5°N. These anomalies support the indications of Figure 26B and 28B that during -/- | EN years: (1) the TEJ is anomalously weak and displaced poleward from its LTM position; and (2) the AEJ is displaced equatorward from its LTM position.

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Figure 33 shows the LTM JAS omega for the same meridional cross section shown in Figures 31-32. In this figure, there are two distinct regions of upward vertical motion. The first is an equatorial region of deep ascent centered between approximately 3°N and 16°N, over TWA and between the TEJ and AEJ. This region of strong ascent has been referred to as the tropical rain belt (TRB) and is thought to be responsible for the majority of JAS precipitation in TWA (Nicholson 2008b).   The second is a subtropical region of ascent centered between 16°N and 20°N that extends only up to 600 hPa. This ascent region coincides with the convergence of low-level winds over land (or the Intertropical Convergence Zone (ITCZ) over land), and is capped by strong Saharan-Sahelian subsidence (cf. Nicholson 2008b). The two regions of ascent are separated by a region of weak descent centered between approximately 11°N to 14°N.
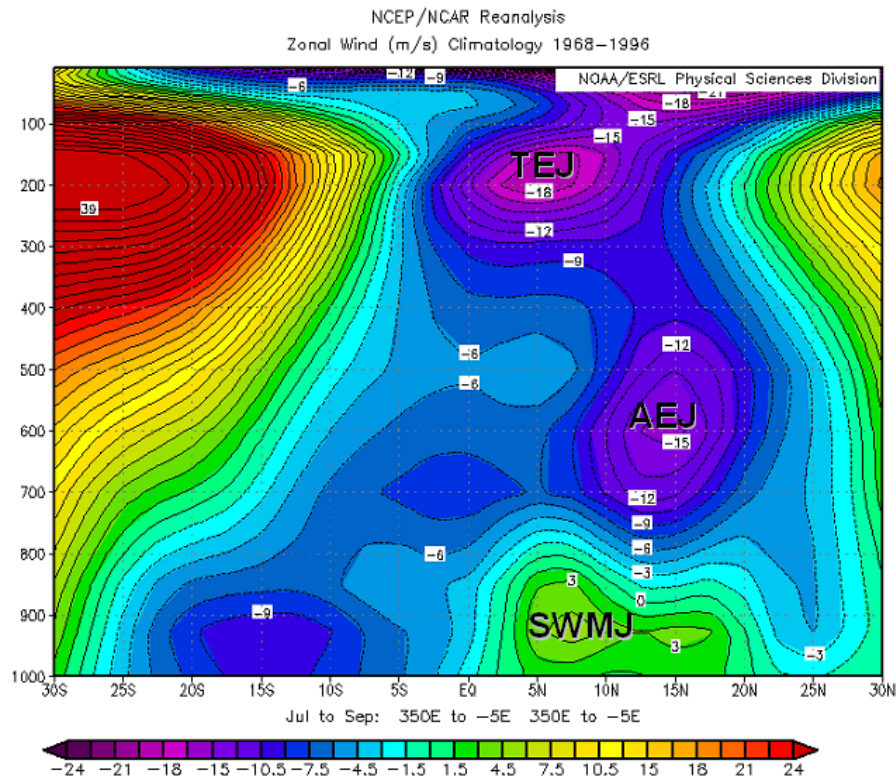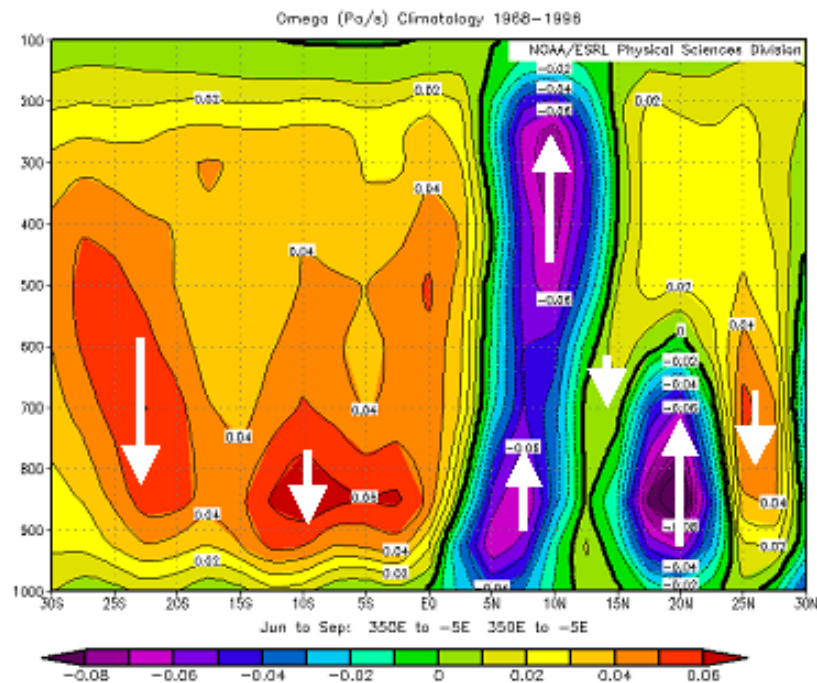

Figure 33.   Meridional cross section of LTM JAS omega (vertical motion) from 30°S to 30°N, and averaged over 10°E to 5°W. TWA occurs between approximately 5°N and 15°N. Zero values indicated by bold black line. Regions of ascent (descent) highlighted by upward (downward) arrows.   Units: Pa s^{-1}.

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Figure 34 shows in meridional cross section JAS omega composite means (*not* omega composite anomalies) over TWA for the +/+ | LN years (panel A) and -/- | EN years (panel B). In the +/+ | LN, the equatorial region of deep ascent seen in the LTM case (Figure 33) extends over a larger latitudinal range and is stronger, especially between the levels of the AEJ and TEJ. Additionally, the equatorial region of ascent merges with the subtropical region of ascent (centered at approximately 20°N) such that deep to mid-level ascent occurs from about 3°N to approximately 25°N. This ascent is consistent with increased JAS rainfall throughout this region (cf. Figures 15, 19).
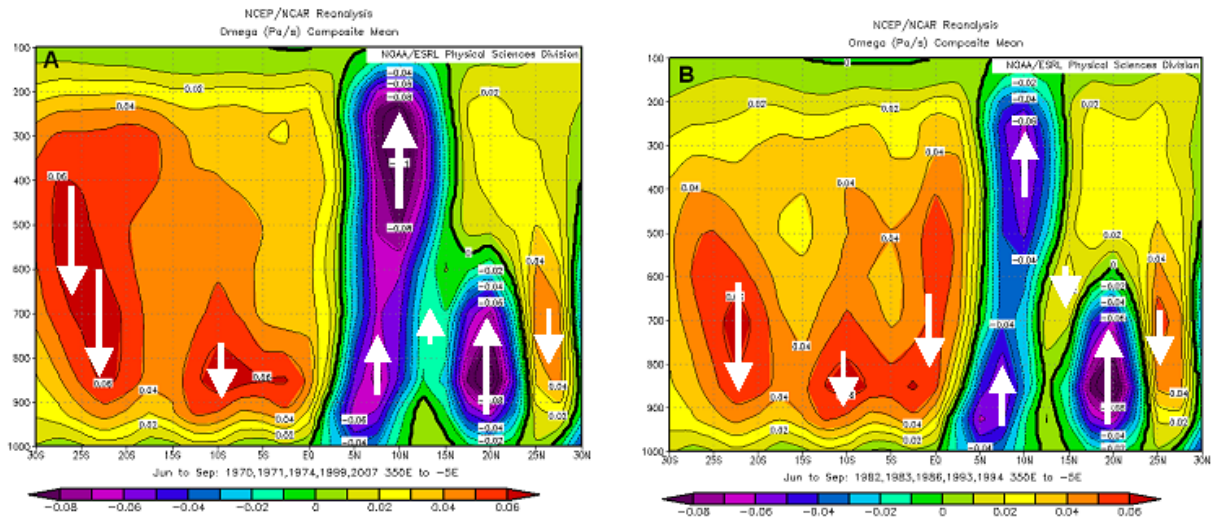
Figure 34.   Cross section of (A) composited +/+ | LN years, (B) composited -/- | EN years of JAS omega, or vertical motion, for a longitudinal band from 10° to 5°W. The dark black line corresponds to the zero contour line and aids in the visual separation of ascending motion from descending motion. Meridional cross section of JAS omega (vertical motion) composite means for (A) +/+ | LN years, and (B) -/- | EN years. Cross sections extend from 30°S to 30°N, and are averaged over 10°E to 5°W. TWA occurs between approximately 5°N and 15°N. Zero values indicated by bold black line. Regions of ascent (descent) highlighted by upward (downward) arrows. Units: Pa s^{-1}.

In the -/- | EN case (Figure 34B), the equatorial region of deep ascent seen in the LTM case (Figure 33) extends over a smaller latitudinal range and is weaker, especially between the levels of the AEJ and TEJ. Additionally, the

equatorial region of ascent is more clearly separated from the subtropical region of ascent. These differences with respect to the LTM are consistent with decreased JAS rainfall in TWA (cf. Figures 15, 20).

To further explore the influence of ENLN on TWA rainfall, we examined the spatial patterns of correlation between the MEI and 300 hPa omega over TWA. The 300 hPa level was chosen because it is the level at of maximum omega during JAS and lies between the levels at which the TEJ and AEJ, and variations in the TEJ and AEJ, are strongest (cf. Figures 33-34). The correlations in which MEI leads by one season and zero seasons both show significant positive correlations between the MEI and 300 hPa omega over most of TWA, particularly over the Sahel (Figure 35). This indicates that LN (EN) events are associated with wet (dry) JAS periods in TWA. These results also support the hypothesis that EN and LN events may be useful long lead predictors of TWA rainfall.
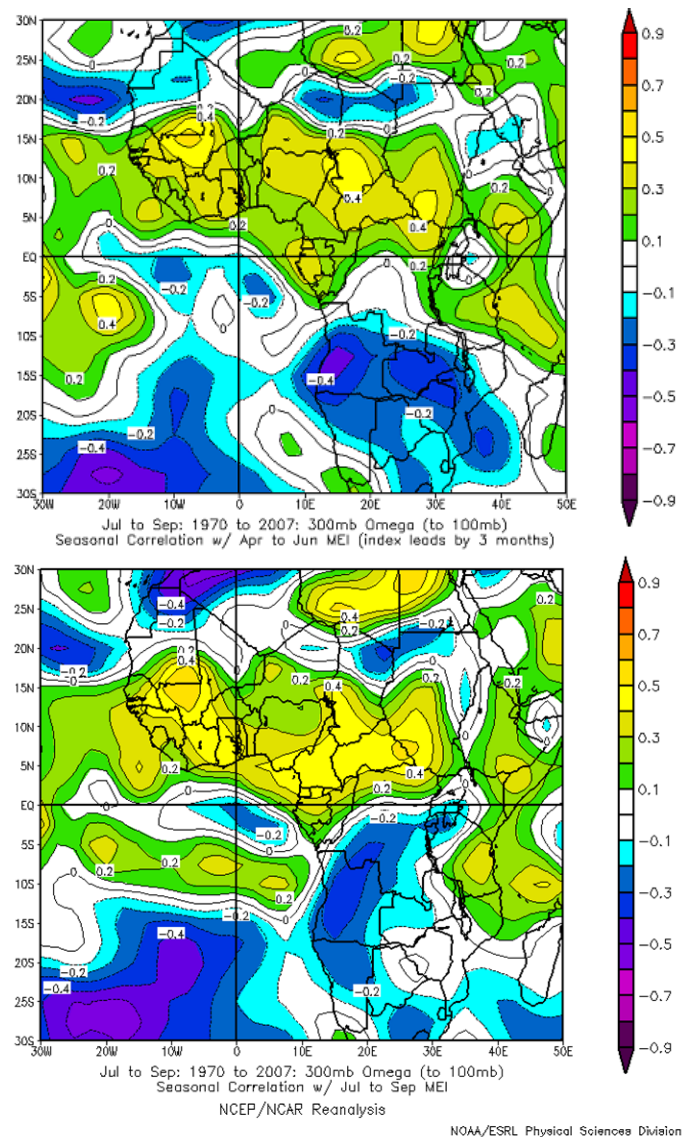
Figure 35.   Linear correlation between JAS 300 hPa omega and (A) AMJ MEI and (B) JAS MEI, for the period 1970-2007. Correlation coefficients greater (less) than 0.3 (-0.3) are significant at the 90% level.

D.   CORRELATIONS TO GLOBAL AND REGIONAL SST

EN and LN events are coupled atmosphere-ocean phenomena. The sea surface temperature (SST) anomalies associated with EN and LN events develop early in the life cycle of an event, and persist throughout the event. In addition,

Nicholson and Webster (2007) cite the influence of tropical Atlantic SSTs in the moderation of surface pressure gradients and, thereby, the amount of rainfall in Africa. Thus, it is important in searching for predictors of TWA rainfall, to examine its relationships to global SST variations. Figure 36 shows the AMJ and JAS SST composite anomalies for the +/+ | LN years and -/- | EN years. The AMJ and JAS +/+ | LN cases (Figure 36A and C) show warm (cool) SST anomalies in the far western (central-eastern) tropical Pacific, as expected for LN events. In the tropical Atlantic, there is an approximately pattern, with cool (warm) SST anomalies in western (eastern) tropical Atlantic. The AMJ and JAS -/- | EN cases show approximately opposite SST anomalies in the tropical Pacific and Atlantic basins (Figure 36B and D). These results support the hypothesis that EN and LN may be good predictors of TWA rainfall, and raise the possibility that tropical Atlantic SSTs may also be good predictors of TWA rainfall.
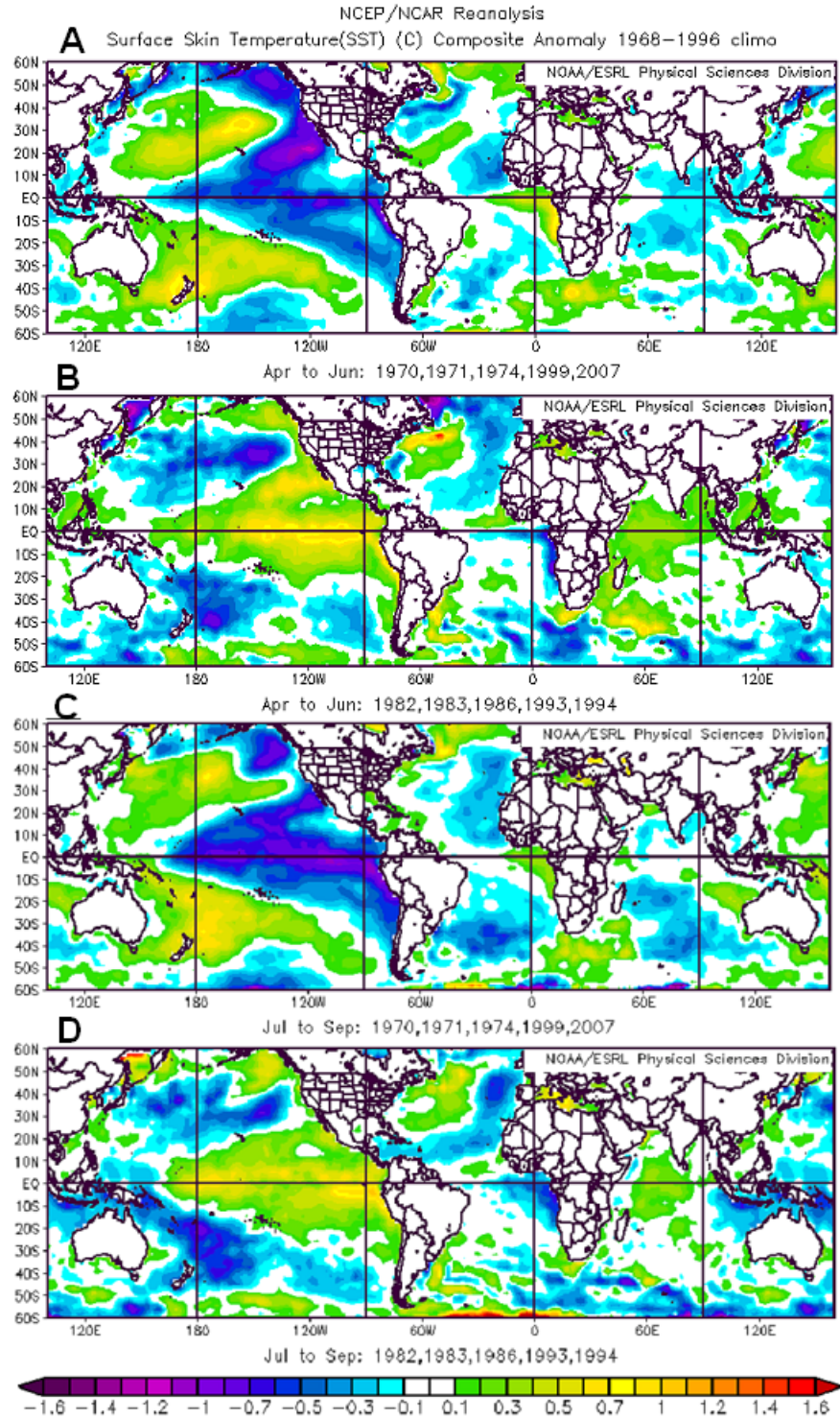
Figure 36.   SST composite anomalies for: (A) AMJ during +/+ | LN years; (B) AMJ during -/- | EN years; (C) JAS during +/+ | LN years; (D) JAS during -/- | EN years. Units: ^{o}C.

Figures 37-38 help explore this possibility by showing more detailed versions of the tropical Atlantic SST anomalies shown in Figure 36. The AMJ anomalies in the eastern tropical Atlantic are noticeably stronger than those in JAS for both the +/+ | LN case and the -/- | EN case, particularly along the coast of Angola and northern Namibia. This supports the hypothesis that SSTs in this region may be useful predictors of TWA rainfall in JAS at leads of up to one season.
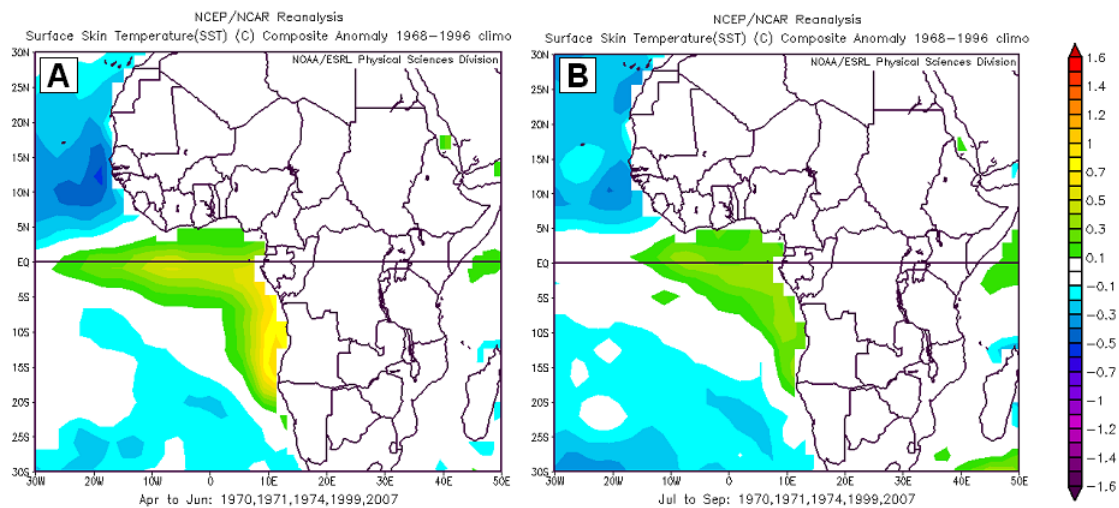
Figure 37. SST composite anomalies for +/+ | LN years for (A) AMJ, and (B) JAS. Units: ^{o}C.
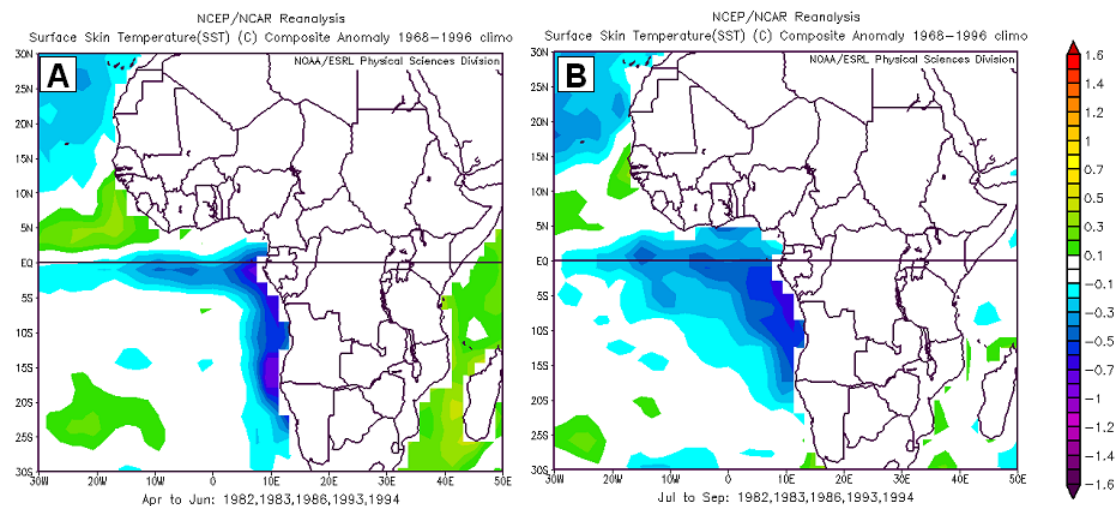
Figure 38. SST composite anomalies for -/- | EN years for (A) AMJ, and (B) JAS. Units: ^{o}C.

The results shown in this chapter indicate that TWA rainfall during the peak rainfall period, JAS, is teleconnected to ENLN via equatorial Rossby-Kelvin waves and extratropical Southern Hemisphere Rossby wave trains. These low frequency wave processes alter circulations in tropical Africa, which in turn alter the low level moisture advection into TWA and vertical motion over TWA. The net result is that there is a strong tendency for TWA-wide rainfall anomalies during JAS to be positive (negative) during LN (EN) events. The timing of EN and LN events is such that they develop during the northern spring and intensify during JAS. Thus, EN and LN events have a high potential for improving long lead (monthly to seasonal) predictions of TWA rainfall during JAS. In addition, SSTA anomalies in the eastern tropical Atlantic also appear to have a high potential for long lead predictions of TWA JAS rainfall.

VI. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

TWA is a dynamic and engaging region, which has increasingly drawn the attention of climate researchers. The region is also becoming of greater interest to the US DoD and other US government agencies. If the United States intends to effectively meet its stabilization objectives for Africa, immediate and dedicated attention must be given to understanding the climate dynamics that so dramatically affect the livelihoods of most of the African population.

This research has been extensively aided by the decades-long work of Dr. Sharon Nicholson who has dedicated the bulk of her research to the understanding of rainfall in TWA. The advances of Dr. Nicholson and others in the understanding of climate dynamics responsible for interseasonal, interannual and interdecadal variability of TWA are admirable. We hope that the results of this study will also contribute to the growing body of knowledge on African climate variations.

These results can be summarized as follows:

- There is a strong correlation between ENLN and anomalously wet and dry years in TWA from 1970 to 2007.

- The ENLN atmospheric response in the central and eastern Pacific Ocean is teleconnected to TWA rainfall via equatorial Rossby-Kelvin waves, and SH Rossby wave trains.

- JAS TWA rainfall is related to SSTs in the Gulf of Guinea and along the coast of Angola and northern Namibia.

- There is merit in restricting a climate analysis of TWA to no earlier 1970, thereby separating recent climate patterns and processes from those that existed prior to the climate shift in the late 1960s.

- The stability of TWA nations is socially and economically tied to TWA rainfall and hence to ENLN.

- Understanding climate variability in TWA rainfall is important for the US government, because:

- The Department of Defense is mandated to incorporate climate research in mission risk assessment, defense planning, and the development of new capabilities needed to reduce the future impacts of climate change, as legislated by the NDAA 2008.

- The Department of Defense is actively engaged in TWA, locally is via the Global Fleet Station concept and regionally via the US Africa Command.

- Military resource and budget planning for missions to be conducted in TWA in five to ten years is occurring now. Those missions will be performed in an area of climate fragility and, to this date, no account has been paid to that fact in mission or resource planning.

- Further understanding of the relationship between ENLN and climate variability in TWA may aid weather forecasters and climate researcher in the prediction of rainfall in TWA.

B.   POTENTIAL IMPACTS OF CLIMATE PREDICTIONS ON MITIGATING POLITICAL AND ECONOMIC INSTABILITY IN WESTERN AFRICA

Diamond (2005) described five factors that contribute to a society's environmental collapse. The five factors are: (1) environmental damage inadvertently inflicted by people; (2) climate variations and climate change; (3) hostile neighbors; (4) decreased support by friendly neighbors; and (5) inadequate societal responses to environmental problems.

The conclusions of our study do not suggest that the societies of TWA are on the verge of environmental collapse, but environmental disasters are already commonplace in Africa. Cursory reviews of the news headlines or internet-published materials on the region indicate that many of the nations in TWA have at least several of the five factors occurring now. Diamond (2005) cautions that a society need not have all five factors operating to face collapse.

Our study is not the only to warn of a dire set of societal consequences for western Africa from climate variations and climate change. Goodman et al., (2007) stated that projected climate change in Africa could present serious threats to even the most stable governments. The tensions wrought by the

deficit of resources required for survival (particularly water), added to the existing instability in most nations in TWA, may exacerbate the crises in the region to a level beyond that which the US military is capable of responding via a Phase 0 - shaping and stability mission.

The mitigation of the impacts of climate change is already forecasted to cost billions of dollars in the United States (Mendelsohn and Neumann 1999; Stern 2006). Considering that the economies of most African nations are minuscule compared to the US economy, monetary support for mitigation strategies from local African governments may be non-existent in the future, along with support from first world donors dealing with their own climate related crises. Additionally, climate adaptation strategies employed in past decades by the two most important rural populations, pastoral nomads and agro-pastoralists, have recently caused the two groups to come into conflict as is the case in the Darfur region of Sudan (Flint and DeWaal 2005).

Sadly, the projections of future climate in TWA, especially for rainfall in the Sahel region, are not favorable. As addressed in Chapter I, the IPCC-FAR has projected a decrease in rainfall in the Sahel region through the next several decades, and an increase in rainfall in the Guinea coast. The time series constructed for this research tends to agree with that assessment. Figure 39 shows a subset of the JAS PRATE time series shown in Figure 14. The JAS time series for the Sahel and Guinea coast in Figure 39 begins in 1970 and is linearly extrapolated out to 2017. Notice that the Guinea coast (Sahel) trend line and extrapolation have a positive (negative) slope, indicating a future JAS PRATE greater (less) than the 1970-2007 mean for the region. These extrapolations of the linear trend for the last 38 years are interesting, but they are by no means a climate projection. However, they are consistent with the IPCC-FAR projections based global climate modeling, and suggest that some of the impacts on TWA of climate change associated with global warming may already be evident.
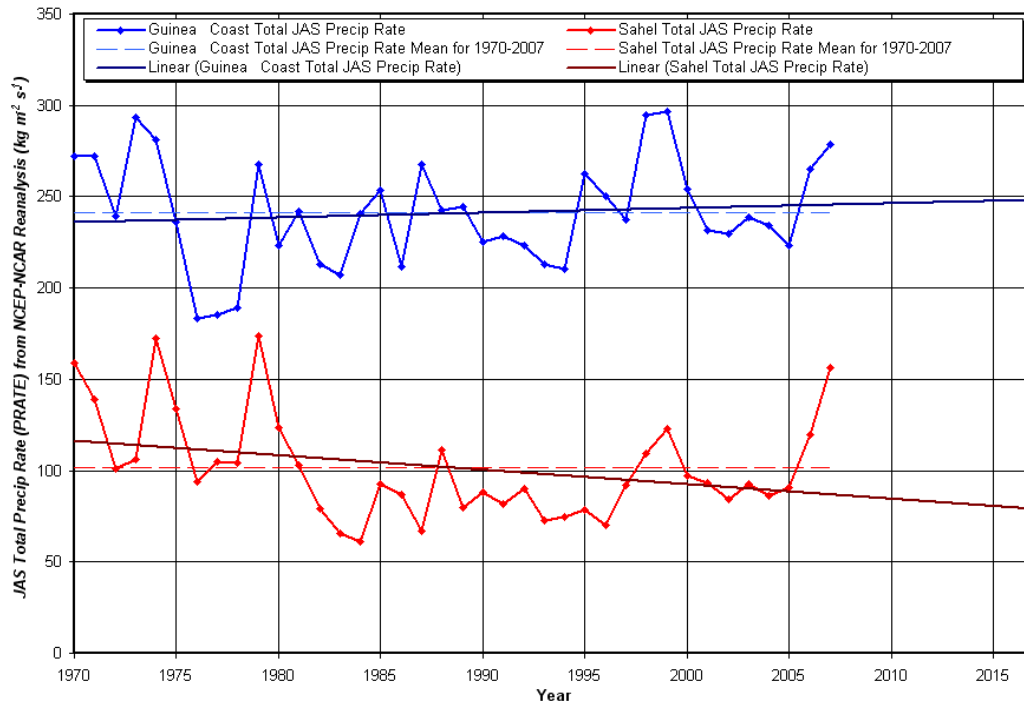
Figure 39.   JAS PRATE time series for the Sahel and Guinea coast regions from 1970 to 2007, with: (a) 1970-2007 means (dashed horizontal lines) and (b) linear trend projections to 2017 (solid sloping lines).

The results of this study, combined with the extensive work of others in the fields of climate science, national security, political science, and defense organization and planning should lead readers to not only an appreciation of the complexity of the environmental consequences at hand for TWA, but also towards an improvement in their understanding and application of mitigation strategies. "Africa's Sahel region is "ground zero" for countries trying to cope with climate change, but sufficient investment in adaptation measures and greater cooperation between neighboring States means this does not have to lead to conflict" (Egeland 2008). The benefits of this research for the general stakeholder are outlined in Figure 40. The last benefit listed under the heading "ALL TERM BENEFITS" (Increased stability in TWA) is the regionalized version of the proposed mission objective of the US AFRICOM for all of Africa.
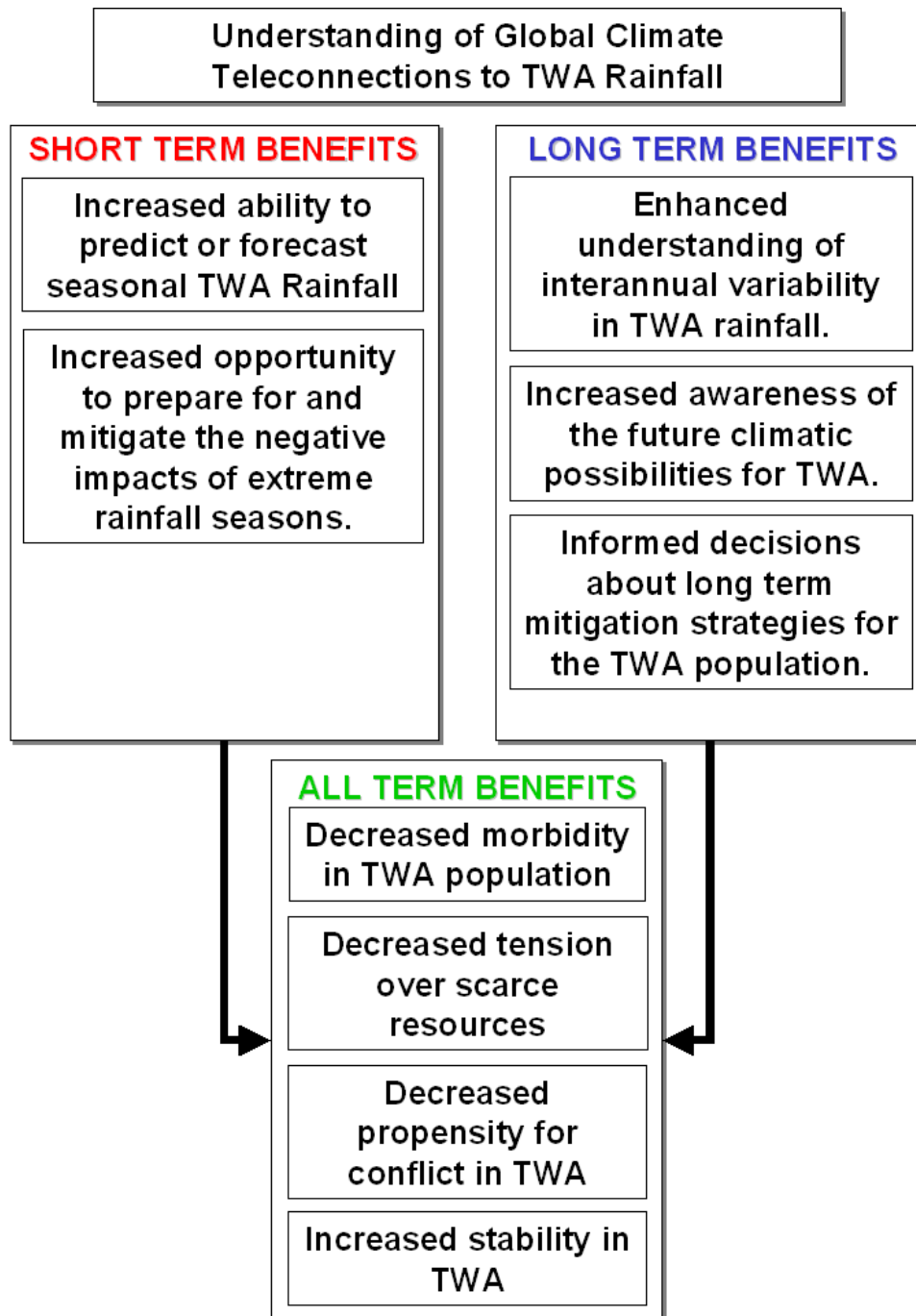
Figure 40.   Proposed high level benefits of understanding global climate teleconnections to TWA rainfall.

C. SUGGESTIONS FOR THE DEPARTMENT OF DEFENSE

1. Identify and fill the gaps in the current knowledge and capabilities of DoD METOC organizations.

A bottom-up review of the current climate resources available within the DoD should be conducted and a joint resource list should be compiled and hosted by the 14th Weather Squadron and FNMOD. The current frontier of research in the civilian sector should also be established and DoD climate knowledge and capabilities should be compared to those in the civilian sector to identify critical gaps and methods for filling those gaps.

2. Actively engage staff METOC officers at AFRICOM in promoting the operational application of state-of-the-science climate information.

The Staff METOC Officer for AFRICOM must work to gain an understanding of the implications of future climate change for Africa and must dynamically engage the Intelligence and Knowledge Development, Strategy, Plans and Programs, and Operations and Logistics Directorates to disseminate knowledge critical to the accomplishment of the AFRICOM mission. Figure 41 is suggestive of the course of this type of engagement, with the ultimate goal of a stable Africa.

LONG TERM BENEFITS	US foreign policy and military strategy for promoting a stable and secure African environment that includes an assessment of the risks of future climate change and addresses mitigation strategies through capacity building per the US National Defense Authorization Act 2008.
Enhanced understanding of interannual variability in TWA rainfall.	
Increased awareness of the future climatic possibilities for TWA.	
Informed decisions about long term mitigation strategies for the TWA population.	

Figure 41.   A continuation (from Figure 36) of the high level benefits of understanding global climate teleconnections to TWA rainfall, especially the benefits to US civilian government and military organizations.

D.   FUTURE WORK AND RESEARCH

1.   Address the climate dynamics associated with the dipole modes of TWA rainfall classification to determine regional and/or global teleconnections.

2.   Examine the role of equatorial Rossby-Kelvin waves and extratropical Southern Hemisphere Rossby wave trains in determining the impacts of EN and LN events on tropical cyclone activity in the North Atlantic (cf. Ford 2000; Hildebrand 2001). Special attention should be paid to the work of Nicholson (2008b) that may change the paradigm of convective activity associated with the ITCZ over TWA.

3.   Examine climate variations affecting the variations in TWA dry season rainfall.

4.   Perform composite and correlation analyses for other regions of Africa (e.g., East Africa, Southern Africa).

5.   Perform correlation analysis for other, well-established climate indices and all of the modes of rainfall classification for TWA.

6.   Explore the importance of the role of wave interference between equatorial R-K waves and extratropical SH Rossby waves over the tropical Atlantic-Africa region.

7.   Examine the relevance and usefulness of a stability index developed as a decision analysis tool in conflict prevention for TWA. The index might include such factors as the occurrence (or non-occurrence) of ENLN, the success of the most recent agricultural season. Data to focus on for the development of an index should be relevant, collectable, and measurable.

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